ELECTRICAL ENGINEERING

Registered U. S. Patent Office

SEPTEMBER

1942

The Cover: The electrical-manufacturing industry produces equipment vital to many phases of the war effort. Here the commutator of a 5,000-horsepower steel-mill motor is being assembled.
Photo Courtesy Westinghouse Electric and Manufacturing Company

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VOLUME 61
NUMBER 9

Statements and opinions given in articles and papers appearing in *Electrical Engineering* are the expressions of contributors, for which the Institute assumes no responsibility. ¶ Correspondence is invited on all controversial matters.

Published Monthly by the

AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS

Founded 1884

HAROLD S. OSBORNE, President H. H. HENLINE, National Secretary

PUBLICATION COMMITTEE: Howard S. Phelps, *chairman*; C. E. Dean; F. Malcolm Farmer; H. H. Henline; K. B. McEachron; John Mills; A. G. Oehler; P. H. Pumphrey; H. H. Race; S. B. Williams

HIGH LIGHTS . .

Overloading Transformers. Tests have been made of effects of time and temperature upon transformer insulating materials immersed in oxygen-free oil, protected from exposure to oxygen by means of nitrogen atmospheres with results that include definite evaluations of the effects of acidity on insulation strength; a method of translating given deteriorations of insulation into overloads of given durations has been developed (*Transactions pages 669–73*). The effects of the characteristics of specific apparatus, ambient temperature, load factor, supplemental cooling, and so forth, on load capability of transformers and voltage regulators are considered for both normal and emergency conditions with a view to meeting present and new load requirements, thus conserving critical war materials (*Transactions pages 692–4*). A report on the revision of section 4, Instrument Transformers, of the Proposed American Standard for Transformers, *C*-57, presents the reasons for the establishment of overcurrent requirements of current transformers for relaying service, and for the revised method of specifying the accuracy of instrument transformers for metering service (*Transactions pages 698–706*).

Compression-Type and High-Pressure Cables. Experimental installation of armored compression cable has indicated that the increase in conductor size and temperature range does not hamper the operation of the cable, and that this type of system is well suited for loads of 100,000 kva or more (*Transactions pages 652–7*). Nonleaded high-pressure gas-filled cable can be designed and manufactured to operate with equal success in steel pipe and can be installed without the insulation being harmed by atmospheric exposure or mechanical handling (*Transactions pages 658–65*).

Electric-Powered Pipe Line. A new 1,260-mile petroleum-products pipe line, utilizing 30,000 horsepower in motors, affords flexibility for present schedules and future expansion, safe handling of hazardous petroleum products, co-ordination of electric apparatus to pump requirements, and an efficient system of control (*Transactions pages 638–44*).

Driven Rods and Counterpoises. The relative merits of the driven rod, the continuous-parallel counterpoise, and the radial counterpoise in high-resistance soil were evaluated in a test setup to determine the ground-circuit arrangement best suited to carry lightning currents with a minimum potential across the line insulators (*Transactions pages 628–34*).

New Instrument Jewel. The technique of manufacturing a new jewel for the bearings of electric indicating instruments has been developed, with carefully controlled dimensions and satisfactory impact strength; these jewels can be made in sufficient quantities to replace the large number of sapphires formerly imported from Europe (*Transactions pages 673–6*).

Fault-Detecting Relay. A relay is now available that will recognize the existence of a single-phase-to-ground fault to the exclusion of all other types of faults where the zero-sequence impedance of the system exceeds the negative-sequence impedance by a reasonable margin (*Transactions pages 677–80*).

Nonlinear Series Circuits. A study has been made of the effect of switching time on the current response in a simple nonlinear series circuit with a saturable inductor, and the effect of initial flux linkages in the inductor on the current response during the first few cycles after the switch is closed (*Transactions pages 625–7*).

Poles and Pole Treatment. The necessity for a broader use of available types of poles, particularly in sizes required for joint use of power and communication lines, is pointed out in a paper which discusses pole use, the natural supply of raw material in the forest, and preservative treatment of poles (*Transactions pages 685–91*).

Quality Control. The United States Army Ordnance Department controls quality of munitions during manufacturing, grading, and measurement; its experience has been surveyed from the first experimental application to present plans to encourage nationwide use of the technique in ordnance plants (*pages 449–52*).

Technical High School. The technical high school combines practical laboratory and construction work with a study of mathematics and science, and aims to train boys for constructive work both in industry and engineering college (*pages 452–7*).

Eddy Currents. A simple and accurate method is presented of calculating the paths of the eddy currents and the torque of a relatively thin conducting disk rotating between the pole pieces of a permanent magnet or an electromagnet (*Transactions pages 681–4*).

Transients. A recent field survey of several representative electric-power systems discloses that transient recovery-voltage conditions in connection with the interruption of short circuits are more severe than was previously suspected (*Transactions pages 666–9*).

Control for 40,000-Horsepower Motor. Automatic control equipment developed for a 40,000-horsepower induction motor provides reliable means, by use of proved apparatus, for performing all the necessary starting, stopping, speed control, and protective functions (*Transactions pages 634–8*).

Compressed-Air Breakers. Advantages of the use of compressed air as a source of power to close circuit breakers include flexibility in design and compactness of the unit, avoidance of heavy closing currents, and an increase in breaker speeds, especially in reclosing (*Transactions pages 695–8*).

AIEE Wartime Policies. AIEE wartime policies have been formally defined and clarified with emphasis on the co-ordination of Institute activities with the war effort (*page 477*).

Switchgear Standards. Standard test voltages for indoor and outdoor circuit breakers, disconnecting switches and bus-bar supports, and assembled switchgear have been formulated by the AIEE protective devices committee (*pages 478–9*).

Engineering and Public Service. In a time when values need to be clearly defined, the views of several outstanding persons on the engineer and the engineering method are of more than usual interest (*pages 465–8*).

High-Frequency Concepts. Characteristics of electricity when the frequency of alternation reaches the range of billions of cycles per second are examined in relation to some basic electrical concepts (*pages 461–4*).

Pilot-Wire Circuit Protection. A new tool has been analyzed, the two-winding neutralizing transformer for dissipating disturbing voltages that are frequently impressed on pilot-wire circuits (*Transactions pages 645–52*).

Substitute Materials in Fluorescent Lighting. High-intensity fluorescent local lighting in many manufacturing plants have light-hoods or reflectors which are now made of fibrous materials in place of steel (*pages 458–60*).

Control of Load Swings. A new method of dispatching generator load changes which considerably reduces the magnitude and occurrence of load swings has been devised (*Transactions pages 623–4*).

Powder Metallurgy. Tests with powder metallurgy have revealed the relative importance of time, temperature, and pressure in the sintering of various materials (*pages 468–75*).

Officers and Committees. National AIEE officers and committees, and Section and Student Branch officers chosen by the Institute for the year 1942–43 are listed in this issue (*pages 483–7*).

Electrical Engineering: Copyright 1942 by the American Institute of Electrical Engineers; printed in the United States of America; indexed annually by the AIEE, weekly and monthly by *Engineering Index*, and monthly by *Industrial Arts Index;* abstracted monthly by *Science Abstracts* (London). Address changes must be received at AIEE headquarters, 33 West 39th Street, New York, N. Y., by the 15th of the month to be effective with the succeeding issue. Copies undelivered because of incorrect address cannot be replaced without charge.

Quality Control and the War

LESLIE SIMON

Experience of the United States Army Ordnance Department in applying quality-control techniques to wartime production of munitions has conclusively demonstrated the value of the method, according to an officer in the Department.

MANY PEOPLE who have a technical or friendly interest in quality control ask me: What is the Government doing in the way of quality control? To what uses is it put and in how many places? What is the attitude of the Ordnance Department toward quality control? What benefits does the Government get or hope to get from quality control? I shall present my answers to some of these questions somewhat after the manner in which many people read magazines; that is, first, a brief perusal from the last part to the first, followed by a more deliberate progress from first to last with a knowledge of the direction in which one is moving.

SUMMARY OF QUALITY-CONTROL ACTIVITIES

With the possible exception of one or two of the largest industrial users, the Ordnance Department has more people engaged in the application of quality control techniques than has any other single organization. This high standing not only is true as to numbers, which may include subprofessional or clerical personnel engaged merely in computing data and plotting quality-control charts, but applies in even greater measure to the proportion of highly skilled statisticians who also possess technical knowledge of the sources of their data and who *entertain a wholesome and objective view of the practical engineering end to which their technical skill is merely a means.* I noticed in the last roll call of the Institute of Mathematical Statistics that more members of that organization are employed at Aberdeen Proving Ground than at any other single establishment.

There are three principal uses of the quality-control technique: control of quality of products during the process of production; a highly specialized use termed the control of measurements; and a third use which might be termed quality determination, or grading of product. Control techniques are not confined to the manufacturing arsenal, but extend to the proving ground, the laboratory, and to the central offices of the Ordnance Department. The Ordnance Department's attitude towards quality control, so far as I can judge, consists of definitely favoring it in Ordnance establishments where it has been found to be of practical use, of offering encouragement and aid to independent establishments that wish to attempt its use as a means to produce more and better munitions, and finally of a wholly impartial attitude towards all producers, whether they use statistical methods for quality control or not, as long as they produce good Ordnance products. Wholesome benefits are now being reaped from this technique, not only by way of more uniform products (and uniformity is a most important quality characteristic of munitions) but also in economy and speed in production. The benefits that are hoped for will become obvious with the more detailed discussion of the origin, progress, and plan for further use of quality control in the Ordnance Department.

Essential substance of a talk presented by authority of the Chief of Ordnance, United States Army, at the AIEE North Eastern District meeting, Schenectady, N. Y., April 29–May 1, 1942.

Leslie Simon is a lieutenant colonel in the Ordnance Department, United States Army, and director of the Ballistic Research Laboratory, Aberdeen Proving Ground, Md.

PROCESS CONTROL

The use of quality control in the Ordnance Department began at Picatinny Arsenal about seven years ago. This application was motivated from the top down, which I believe is the manner in which most applications must be motivated. Only the management has the breadth of vision to foresee results and the authority to institute change. The influence for change arose from conversation between the officers in command and Doctor Frank Jewett, then president of the Bell Telephone Laboratories. This first application was characterized by a total absence of statistically trained personnel. However, after a careful study of Doctor Walter A. Shewhart's book,[1] a study of the production lines from the viewpoint of quality control (including many trial runs), and after a great deal of advice most generously given by Doctor Shewhart himself, a quality-control system was devised for the production of munitions which operated successfully without material change for about six years. During the last year, under the able direction of Captain A. C. Cohen, I understand that considerable improvement in the system has been made.

In the clear light of hindsight this first system furnishes an illustration of a good feature that cannot be emphasized too much and of two bad ones that might well be avoided. The good feature is the careful study that was made of the production process and the adaptation of the statistical technique to meet the practical engineering end. Without this objective practicality the experiment almost certainly would have failed, and statistical methods for quality control would have been unceremoniously terminated either by the officer in

charge of the experiment or by his superior officers. The many principles which can be used to guide quality control are so well recognized and established that they have become standardized.[2] But the actual quality-control plan that is put into operation must be tailor-made to the product and process.[3]

One bad feature was the manner of initiation. Partly as a test of the practicality of the system and partly through ignorance, the quality-control system was put into operation on all production lines at the same time. The system was devised, instructions issued, the administrators appointed, and then an order issued that on such and such a day it was to go into effect. It was by extreme good fortune that it did so. A much wiser plan would have been to apply the technique to a few selected production lines under the supervision of a few carefully trained men; to observe it for a period of time in conjunction with the established method of engineering control; to remove the engineering control upon the accumulation of satisfactory evidence that a quality-control technique could carry the load; and, finally, gradually to expand the quality-control technique from production line to production line, along with the gradual training of personnel for its administration. This would have provided a much safer and smoother transition.

The second mistake was a consequence of making the system almost too simple. Because of a lack of better-grade personnel, and in the interest of economy, the procedure was so systemized in detail that practically all of the statistical duties could be performed by personnel of clerical grade. As long as there was no great change in the arsenal, a trained industrial statistician was not needed to administer the system. The mistake consisted of not providing for the presence of at least one industrial statistician. A change in officers allowed the system to fall into the hands of the subprofessional personnel who were gathering the data and posting the charts. This condition resulted in two ill consequences. First, there was no articulate exponent of quality control to gather, codify, and present factual data on its advantages, to present its gains in authoritative form to the management, and to apprise other agencies of its benefits. This condition perhaps more than any other accounts for the fact that other arsenals are now just beginning the use of quality control. Second, the system could not be expanded to meet war conditions until a trained statistician had been employed and had had time to study the manufacturing processes.

QUALITY DETERMINATION

The second use of the quality-control technique by the Ordnance Department was made at the Ballistic Research Laboratory. This use should be regarded as quality determination rather than quality control. The Ballistic Research Laboratory is charged with the surveillance of ammunition; that is, the detection of deterioration in stocks of ammunition and the grading of lots of ammunition in accordance with their quality. With a view to reducing the cost of sampling and to obtaining more accurate information, the Laboratory undertook a study of the control-chart technique for application to munitions. In this new application of quality control the detection of an assignable cause of variation did not call for the discovery and removal of the cause, but for the firing of more samples of the lot of ammunition to determine its quality more accurately. Such a distinctively different use may call for a quite distinct change in the usual concept of action limits, as the balance (see page 11 of reference 3) between the cost of the consequences of looking for assignable causes of variation which do not exist, and of not looking for causes which really do exist, may be considerably altered. After much careful study and many trials in parallel with the old system, the plan was officially investigated by high officials of the Ordnance Department and the statistical method for the surveillance of ammunition was made the official system of the Ordnance Department. This plan has operated successfully for over four years, and the reputation which it has built up for the economy and precision of the statistical method is largely responsible for the existing large-scale use of quality control in the Ordnance Department.

At about the time the surveillance system was getting under way, the officers at the Laboratory and some of the officers at the central office began to realize that the benefits which accrued from industrial statistics were limited by the difficulty of obtaining statisticians with an engineering or physical-science background, not to mention a background in the technical field to which their statistical method is to apply. Therefore, it was decided to gather into the Laboratory some of the best young statisticians obtainable and deliberately train them in technical ordnance, while at the same time having them perform the duties connected with the surveillance system. This move has provided the Ordnance Department with at least a few trained men to meet the pressing demands that now exist.

THE CONTROL OF QUALITY OF MEASUREMENTS

The major activity of Aberdeen Proving Ground is the proof-testing of all arms and ammunition except small arms for the Army. During the development of the surveillance system it became apparent that the statistical method was of great use to the Laboratory in supplying advice to the proof department regarding the more technical phases of this work. Finally, it became apparent that there was a very real need for statistical methods in the control of the Proving Ground's product, namely, measurements. If the Proving Ground's measurements are subject to assignable causes of variations, erroneous conclusions may be drawn with regard to the results of tests. As a result of the wisdom and foresight of the chief proof officer, Colonel George G. Eddy, the

Laboratory was called upon to assist in the design of a system for the control of Proving Ground measurements. This system is similar in many respects to that usually found in the control of quality of manufactured product. It has operated with marked success under the capable and energetic supervision of David Kinsler, formerly of the Bureau of the Census. It operates so as to segregate variations due to materiel being tested from variations due to instruments and personnel. I think it is a marked tribute to this system that the precision of Proving Ground measurements today is slightly better than it was a year ago, especially when one considers that during the past year there has been a huge expansion in personnel. Almost all new personnel are inexperienced and untrained. The statistical method has contributed much in making possible the efficient use of these new people.

THE APPLICATION OF QUALITY CONTROL TO ACCEPTED PRODUCT

By the time the defense emergency began, the evidence gathered from quality control at Picatinny Arsenal, surveillance at the Ballistic Research Laboratory, and control of measurements at the Proving Ground was sufficient to lead to the conclusion that existing acceptance specifications are not a sufficient basis for making the most economic use of procured materials. Therefore the Ordnance Office called upon the Laboratory to provide the necessary quality-control techniques for the Inspection Section of the Ammunition Division. This is a huge task which runs on a huge scale. A separate technique must be provided for each item of ammunition. The results are analyzed in the Ordnance Office in accordance with these techniques and a great deal of important information not heretofore available is brought to light.

THE CONTROL OF QUALITY OF COMPLETE ROUNDS OF AMMUNITION

While the steps just described are another instance of quality determination, they made possible a most effective use of quality control in the war effort. Early in the war effort, two bottlenecks in the procurement of ammunition developed. Bottleneck number one was directly attributable to measures that are taken to insure the uniformity of lots of complete rounds of ammunition. A lot of complete rounds of ammunition must of all things be uniform, otherwise the artillerymen's adjustment of fire is entirely spoiled. The effectiveness of the fighting forces may be distinctly impaired by nonuniform lots. Therefore, it has long been required that each lot of complete rounds contain fuses from one lot of fuses, boosters from one lot of boosters, and so forth, for practically all components, of which there are a considerable number. It is difficult enough to make one's bread and molasses come out even, but when there are a half dozen kinds of bread and molasses, the problem is greatly aggravated. The component lots are generally limited in size to some relatively small number. Therefore, it is easy to see that the complete-rounds manufacturer does not get very far before he exhausts the lot of primers which he is using. This calls for the beginning of a new complete rounds lot. Then he may run out of boosters. Next he may run out of powder, and so forth. Consequently, lots of complete rounds tended to be small. This meant loss of time for the complete-rounds manufacturer, because he had to clear his production lines of all units of the old lot before beginning a new lot. Lot cards had to be printed and closed out. Other essential functions pertaining to the complete-round lot had to be performed. Furthermore, for every lot of complete rounds a sample had to be tested at the Proving Ground, which led to bottleneck number two. The Proving Ground became congested and both production and shipment of ammunition were threatened with delay unless proof-testing could be greatly expedited. These conditions led to a conference at Washington where the troubles were presented and a solution sought.

The statistical technique made the solution easy. The experience gained from surveillance techniques showed that the separation of components, such as fuses, boosters, and so forth, into successive lots was often nothing more or less than periodic division with respect to time. That is, the differences between lots were no greater than differences within lots. However, lot sizes had to be limited because no one could foretell how long the manufacturer could continue to make articles that were essentially alike. With the statistical technique set up in the inspection section of the Ammunition Division it was quite easy to tell how many lots a manufacturer had made that were essentially alike. An aggregation of lots that are essentially alike is termed a grand lot. Therefore, all the Ordnance Department had to do was to capitalize on its statistical technique, and instead of requiring, for example, that all fuses in one lot of complete rounds be of the same lot, require that all fuses be of the same grand lot. This enabled production of large lots of complete rounds without any loss in uniformity. It saves time and money to the complete-rounds manufacturer, saves time and money in testing at the Proving Ground, relieves congestion at both places, and provides the artillerymen with bigger and better lots of complete rounds.

RECENT DEVELOPMENTS IN THE ORDNANCE DEPARTMENT

The most recent development in the Ordnance Department is attributable to Doctor Shewhart, Captain Cohen, and several others who talked together at the last meeting of the Institute of Mathematical Statistics. They realized that they, the Laboratory, and the Proving Ground were being burdened with a large number of questions from various persons and establishments re-

garding the use of quality-control techniques in war industry. As a result of their initiative, a letter was written by the Commanding General of Picatinny Arsenal which resulted in a conference at the Ballistic Research Laboratory which, in turn, resulted in calling this condition to the attention of the Chief of Ordnance. There has now been established in the office of the Chief of Ordnance an organization, under the direction of G. D. Edwards of the Bell Telephone Laboratories, for co-ordinating the efforts of various departments and establishments with respect to quality-control techniques. All divisions of the Ordnance Office and all establishments employing quality control have representatives for contact with this organization. In this way, an exchange of ideas is effected, assistance in difficult phases of problems is obtained, and inquiries from various sources are passed along to the central body for authoritative answers.

FUTURE DEVELOPMENT OF QUALITY CONTROL

Present progress has been so fruitful that plans are now under way definitely to encourage quality-control techniques in the establishments under the control of the Ordnance Department. The next step probably will consist of having each Ordnance district, of which there are 13 blanketing the country, appoint officers and civilians as quality-control representatives and to give these representatives a brief course in the principles of the quality-control technique. These men will provide a leaven or nucleus of quality-control men in their respective districts, to review critically the results of inspection of material, to criticize inspection practices and establish better ones, and to organize quality-control methods on selected lines in various munitions industries. From these, the quality-control method of inspection can be spread line by line until its benefits are extended at least to the greater percentage of those inspection operations where it may prove effective.

THE ASA AND QUALITY CONTROL

Attention should be called to some of the factors that have contributed to the extensions of the benefit of quality control to the war effort. Aside from the collective effort of the individuals who work in this field, I believe that the greatest single contribution has been the action taken by the American Standards Association in issuing the new Emergency Defense Standards for quality control. Without such official recognition on the part of that authoritative agency I doubt if the higher officials of the Ordnance Deparument could have been persuaded to take the action just described.

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1. The Economic Control of Quality of Manufactured Product, W. A. Shewhart. D. Van Nostrand, New York, 1931.
2. Guide for Quality Control, Z1.1—1941. American Standards Association, New York.
3. Control Chart Method of Controlling Quality During Production, Z1.3—1942. American Standards Association, New York. Presents detailed guiding principles.

The Technical High School Trains for Life

C. E. CROFOOT
MEMBER AIEE

THE technical-high-school movement has been growing steadily throughout the United States and Canada for the past 25 years. However, it has apparently been stronger in the East than in the West, probably because of the heavier concentration of industry in the eastern cities, since the technical high school trains directly for industry. The enrollment in these schools jumped considerably after the last war and it has risen sharply during the past two years. The total technical-high-school enrollment for New York State rose from 309 in 1921 to over 15,000 in 1942. Similar increases probably have been shown in other states. They were caused in large measure by the efficient training provided by these schools and the more effective laws regulating them.

The primary aim of the Mont Pleasant Technical High School at Schenectady, N. Y., is to train boys to become efficient members of the group of technicians, service men, and junior assistants to engineers, architects, and service production managers in the highly technical or junior-engineering branches of industry. Our curricula are, however, so designed that the cultural side is not neglected. We feel they should be so planned that the door to college is kept open for those who can afford or profit by it and that any course, either academic or technical, should build good citizens.

Our technical curricula are naturally designed to provide a good foundation in mathematics, science, drafting, and technology, which are all essential to future growth in the technical fields of modern industry. They also require the same high-school English, history, and economics that are found in our college-preparatory academic courses. Only the foreign language is left off the required list, to make room for some of the technical subjects.

Essential substance of a paper presented at the AIEE North Eastern District meeting, Schenectady, N. Y., April 29–May 1, 1942.

C. E. Crofoot is head of Mont Pleasant Technical High School, Schenectady, N. Y.

The technical student also spends considerable time in the shop and laboratory, so that he learns by doing. As a result, our graduates can enter either industry or engineering college with equal facility. The technical students attend school one hour per day longer than do the academic students.

The technical high school is not a technical institute, even though much of our instruction and laboratory equipment are patterned after those of the institute. Our students are accepted directly from the junior high school, while the technical institute accepts them from the senior high school only. The work, however, is all of high grade and can be mastered only by the better students. They must have a mathematical and scientific turn of mind or they will fail.

Based on the belief that boys interested in engineering should have an opportunity to do practical work at the same time that they are learning the elements of mathematics and science, technical-high-school curricula, as exemplified in Mont Pleasant Technical High School, Schenectady, N. Y., have proved very successful in preparing students for work in local industries. The same courses have also shown their effectiveness as preparation for engineering college.

NEED FOR A TECHNICAL HIGH SCHOOL

Changes in methods of production, increased use of power, and invention of labor-saving machines have brought about a very definite need in most industrial communities for boys of technical-high-school grade. In fact, several technically trained men of less than college grade are required for each engineer. This is particularly true in centers like Schenectady. The technical-high-school graduates will often do a better job than the engineering graduate would on much of the practical but very important developmental work in general-engineering and research laboratories, because they have more skill in the actual handling of equipment and also because they are relatively more adapted to such jobs.

For this reason, the most successful technical high schools are those which maintain very close co-operation with local industries. This brings up one of the most distinct differences between the technical high school and the engineering college. The average college places the larger percentage of its graduates in industries far removed from the college, and those industries have a wide diversity of requirements. Practically all the technical-high-school graduates are placed in the immediate vicinity of the school from which they are graduated. The reaction to poorly trained graduates is, therefore, quick and fatal, if the school has not adapted its technical training to the needs of local industries through careful co-operation. Technical training must also be fundamental enough that the employer can shift the boys from one job to another when conditions make this necessary.

PRINCIPAL TYPES OF TECHNICAL HIGH SCHOOLS

There are two general types of technical high schools in operation in New York State. The first type is found in such cities as New York, Yonkers, Rochester, and Buffalo, which are large enough to support separate buildings, and have funds and students enough to make them effective units. The second, and more common type, is the comprehensive high school, like Mont Pleasant Technical High School, which is really a school within a school. The technical group usually numbers around 400 boys out of a school averaging about 1,900 students, with the academic section about equally divided between boys and girls. A school of this size can offer many more opportunities for leadership and extracurricular activities than would be possible with a unit of only 400 boys and no girls to balance a social-activity program.

It is, of course, true that an unsympathetic academic principal can exert a depressing or retarding influence on the technical group, but fortunately such cases are few if the technical department does a thorough job of training. We are extremely fortunate in Mont Pleasant High School in having a broad-minded academic principal who has maintained a very sympathetic attitude toward our technical group. He has recognized from the first that only boys of the highest mental caliber can handle the technical work and has been a great help by constantly steering good boys with a scientific and mathematical bent into our courses. He has taken pride in the fact that about one third of the graduating-class presidents have been boys from the technical course.

There are some disadvantages in fitting the technical and academic daily schedules together, due to the longer technical day and double shop or laboratory periods, but a wholesome co-operation between the faculties of both parts of the school will overcome these difficulties. The main advantage is that of having the technical boys take their English, history, economics, and other non-technical courses, in the same classes with the academic boys and girls. Thus each group has a chance to see that there is nothing peculiar about the other. Each group is a good check on the other. This cannot be done if the groups are in separate buildings. The comprehensive school also affords an opportunity for any technical boy to take a foreign language as an extra subject if he wants it for entrance to some particular college, or for its cultural value. It also shows the college-preparatory student that only boys with the highest mentality can handle the technical course. When they are in separate buildings the college-preparatory student is likely to look down on the technical student. This way he is forced to compete with the technical boy and finds him more than a match.

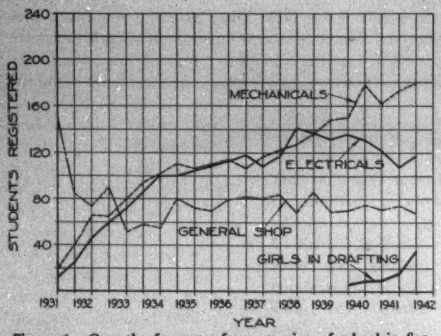


Figure 1. Growth of courses from opening of school in September 1931, to date. Mechanical group shows influence of war

There is relatively much more in common between a senior academic high school and a technical high school than between an industrial vocational high school and a technical high school. The industrial high school attracts boys who are more "hand-minded" than mathematically or scientifically inclined, so the emphasis must be placed on training in manual skills. When these students are combined with a technical group, the result is usually to lower the standard of the technical school.

TRAINING GIRLS IN DRAFTING

The present war emergency has shown another distinct advantage of the comprehensive high school. When industry called for girls to work as tracers and clerks in drafting rooms it was an easy matter to enroll a number of girls from the commercial and other academic groups for training in the drafting classes. Over 85 per cent of these girls have been placed in drafting positions during the year and a half and our enrollment has increased each term.

TYPE OF INSTRUCTOR REQUIRED

It is very difficult to find good technical teachers. New York State requires an engineering education, plus at least three years of practical engineering experience in industry after graduation. The men must also add 18 hours of teacher training at colleges which meet the state requirements for this work. These requirements help assure a better theoretical and practical training for technical boys, as well as better vocational guidance which is the result of actual industrial experience.

The technical instructor must be prepared at all times and must know his subject so well that he will command respect from his students. The best all-around electrical instructor is the man who has been a service-shop or road engineer for some manufacturing company. He has had to make things work in the field under difficulty, and to correct the mistakes of the designing engineers so that the customer will be satisfied. Such experience develops resourcefulness and a wealth of information about the application of electricity to a number of other industries. This accumulated information broadens an instructor so he can then train boys for more than one branch of electrical work.

An instructor with this experience and background can be of invaluable help in guiding boys into lines of work for which they are particularly well adapted. He can also analyze them and help the principal to write recommendations that will be of real value to an employer in placing a boy in the right department.

IMPORTANCE OF LABORATORY AND SHOP EQUIPMENT

Next to the instructor comes the equipment, as both are essential to a successful technical high school. The best-trained instructors will fail without complete, well-chosen equipment with which to work. Two things must be borne in mind in selecting the equipment for such schools: first, that the instruction must emphasize the application and use of apparatus; second, that a technical-high-school boy spends relatively much more time in the laboratory and shop than does the average college student. In the first place, a student learns more about the characteristics of a piece of apparatus by actually working with it than in any other way. Unless sufficient equipment is provided to keep the whole class working all the time, the instructor will have a serious discipline problem and will turn out a shiftless lot of boys because they have learned to loaf in the laboratory.

EFFECTIVE APPRENTICE TRAINING

The technical high school, with its experienced instructors, practical equipment, and drafting rooms is of great value in a community as a co-operative training center for local industries.

For example, the technical-high-school faculty and equipment are both especially well adapted for industrial apprentice instruction which should be carried on

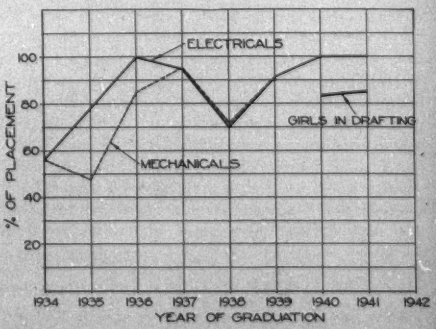


Figure 2. Placement of graduates from first class in 1934 to date

Table I. Apprentice Training Curriculum

Term		Hours Per Week	Term		Hours Per Week
	First Year			**Second Year**	
I	Shop mathematics I	2	I	Trigonometry I	2
	Algebra	2		Mechanics (shop)	2
	Drawing	2		Metallurgy	2
II	Shop mathematics II	2	II	Trigonometry II	2
	Geometry (plane)	2		Machining of metals	2
	Drawing	2		Strength of materials I	2
III	Shop mathematics III	2	III	Descriptive geometry I	2
	Physics (advanced)	2		Mechanics I	2
	Drawing	2		Strength of materials II	2
	Third Year			**Fourth Year**	
I	Descriptive geometry II	2	I	Machine design II	2
	Mechanics II	2		Analytic geometry I	2
	Electricity I	2		Electricity IV	2
II	Mechanics III	2	II	Machine design III	2
	Kinematics I	2		Analytic geometry II	2
	Electricity II	2			
III	Machine design I	2	III		
	Kinematics II	2			
	Electricity III	2			
Elective					
Tool and die design					
Calculus					

in co-operation with industry. The actual machine or shop instruction should be given by the industry itself. The following apprentice curriculum, offered by the Mont Pleasant Technical High School, is a good example of this type of co-operative training. The present enrollment in this course is over 500 apprentices, and all classroom training is planned to correlate closely with work at the shop. The apprentice can then put it to immediate use in the shop and thereby clinch it in his mind.

TECHNICAL-HIGH-SCHOOL CURRICULA

The following day-school curricula are offered at Mont Pleasant Technical High School. They are three-year courses designed to follow the ninth grade or junior high school. The mathematics and science are all taught by men who are trained engineers, and who give the subjects a practical application.

These subjects represent a difficult schedule for a boy to carry, but we have always maintained that "cinch courses" will not attract high-grade, ambitious boys and that loafers are not looking for hard work. The truth of our supposition has been borne out by the fact that over 35 per cent of all the boys on the school honor roll come from the technical group, although it includes only 27 per cent of the total enrollment of boys.

A general shop course is offered for boys who cannot handle the exacting work of the technical courses. These boys have no special curriculum requirements, but are allowed to elect their own courses and take what shop work they wish, on sheet metal, wood work, molding, lathe work, and automobile mechanics. Direct placement is very low in this group except in unusual times such as we now have. They are shown on the growth chart as "nontechnical."

The boys are urged to take the state Regents' examinations in English, history, economics, science, and mathematics, to make them readily acceptable in engineering colleges if they later decide to attend college. In addition, a six-hour Regents' comprehensive technical examination is given at the end of the course.

All technical instruction given must be immediately applicable to the future work in industry, or student and employer reaction will be most unfavorable to the school.

BOYS LEARN TO THINK AND BECOME SELF-RELIANT

The technical high school should emphasize the practical use or application of industrial equipment and processes. The design of such equipment is a job for the engineer. For this reason, the technical boy should be trained to use his head and hands together. If he cannot do this, his progress will be slow at first. This is particularly true of the electrical student. If he can build special test apparatus and work out intricate circuits, he is not only a great help to the engineer for whom he works but sooner or later will develop new and useful ideas of his own. This work brings the boys into close association with designing engineers, which is an education in itself.

A thorough technical training in high school helps a boy to develop ingenuity and the ability to analyze a problem and to think logically, as well as to contribute his part to a co-operative enterprise. All of these become natural for him because he must early learn to work in a group of from two to five boys in the laboratory. These groups are put on their own. They must make decisions and be willing to take the responsibility for them, since

Table II. Curriculum for Electrical Students

Entrance Requirements: Pupils must have completed the ninth year in junior high school, including elementary algebra

Term I	Periods Per Week	Term II	Periods Per Week
First Year			
English 10B	5	English 10A	5
Plane geometry B	5	Plane geometry A	5
Applied drafting 1B	10	Applied drafting 1A	10
Electrical theory 1B and electrical shop	10	Electrical theory 1A and laboratory	10
Physical education	5	Physical education	5
Study	5	Study	5
Second Year			
English 11B	5	English 11A	5
Intermediate algebra B	5	Advanced algebra or solid geometry	5
Applied drafting 2B	10	Plane trigonometry	5
Electrical theory 2B and laboratory	10	Electrical theory 2A and laboratory	10
Physics B	7	Physics A	8
Study	3	Study	7
Third Year			
English 12B	5	English 12A	5
American history B	5	American history A	5
Economics	5	Mechanics (with lab.)	10
Electrical applied math	5	Electrical theory 3A and laboratory	10
Electrical theory 3B and laboratory	10	Electronics	5
Study	10	Study	5

Note: Exceptional boys may also elect applied drafting, machine design, strength of materials, chemistry, a foreign language, or other academic subjects instead of study period.

Table III. Curriculum for Mechanical Students

Entrance Requirements: Pupils must have completed the ninth year in junior high school, including elementary algebra

Term I	Periods Per Week	Term II	Periods Per Week
First Year			
English 10B	5	English 10A	5
Plane geometry B	5	Plane geometry A	5
Applied drafting 1B	10	Applied drafting 1A	10
Materials of industry / Machine shop theory	10	Machine shop 1B	10
Physical education	5	Physical education	5
Study	5	Study	5
Second Year			
English 11B	5	English 11A	5
Intermediate algebra B	5	Advanced algebra or solid geometry	5
Applied drafting 2B	10	Applied drafting 2A	10
Physics B	7	Plane trigonometry	5
Machine shop 1A	10	Physics A	7
Study	3	Study	8
Third Year			
English 12B	5	English 12A	5
American history B	5	American history A	5
Economics	5	Machine shop	10
Mechanical applied math	5	Machine design	10
Mechanics (with lab.)	10	Strength of materials (with lab.)	10
Study	10		

Note: Exceptional boys may elect chemistry, electricity, a foreign language, or other academic subjects instead of study period.

a wrong decision may mean the destruction of valuable apparatus, or injury to a fellow-worker or to themselves. It becomes easier for the graduates to meet people and converse intelligently with them, as well as to remain open-minded. All these things contribute to self-reliance and trustworthiness, based on a level-headed consideration of the facts involved.

The technical student has a distinct advantage in engineering college over the academic college-preparatory student. Since he has used his mathematics and science in his technical work all through high school, they are second nature to him when he reaches college. He knows how to apply them. The academic student simply studies them long enough to pass an examination and moves on to another subject, and the mathematics and science are forgotten by the time he reaches college. The technical boy has also found himself, and knows what he wants to be before he enters college. While we do not train primarily for college, an average of about 12 per cent of electrical and 10 per cent of mechanical students do go to engineering college and more than 95 per cent are graduating in four years, as against half that percentage from academic college-preparatory courses.

The boys seem to enjoy thoroughly the technical curricula, in which there is a balance between the cultural subjects, such as English, civics, history, economics, and the applied technical work. This balancing of subjects adds interest to the day's work, since the wide range of subjects covered tends to break up the frequent monotony of school work. The free discussion of the work in the laboratories between boys of a given laboratory group and between the groups and their instructor helps develop their personalities and the ability to express themselves which is so important in life.

SOME TANGIBLE RESULTS

The foregoing discussion has shown what we are trying to accomplish at Mont Pleasant, and the manner in which we are carrying out our ideas. It therefore may be of interest to offer some comments on the records of our graduates in order to present a picture of the results thus far.

After Mont Pleasant Technical High School was opened in September 1931, with a registration of 12 electrical and 18 mechanical students, the enrollment grew steadily for three years, and thereafter has been maintained at the desired levels as our facilities have been enlarged, with applicants being turned away each year.

The graduation of the first class in June 1934 marked a turning point in the development of the course, for in spite of the depression, nearly 60 per cent secured immediate employment in jobs for which they had trained. The consistently fine records of the first graduates initiated a greater demand from employers, as well as greatly increased the popularity of the course with students. A healthy growth is shown by the graph in Figure 1. It also shows how the war has unbalanced the load between electrical and mechanical groups. They all want to be machinists now, even though we cannot begin to get enough electrical graduates.

Placement of graduates in suitable jobs is an important function of a technical high school. A transcript of the school record of each graduate is sent to all the principal

Figure 3. Boys at work in the electrical laboratory. Motors and projects on table at right are made by boys

employers of the area, together with a very frank, honest and complete appraisal of the student's character, aptitudes, and a summary naming one or two types of work for which he is best qualified.

These recommendations have proved so accurate that they are now much appreciated by employers as well as by students, and have proved an important factor in helping the graduates to obtain positions best suited to their abilities. Graduates are invited to report periodically on their status, and they have done so practically without exception. This practice helps to maintain their interest in the school and also brings us many new recruits. Employers now come to the school ahead of graduation with a list of their requirements.

Records are kept at the school for at least the first three jobs of each boy and the file so maintained contains many interesting personal stories. By this follow-up system, many boys who could not secure just the positions they wanted at first, because of the depression, have later been placed more effectively. Among the hundreds of letters and personal reports that have been received, there is no case of any student's expressing regret that he had taken the technical course rather than some other. Technical-high-school placement records over a period of 20 years show a higher per cent of electrical than mechanical placements when times are poor, as there are more places where one can obtain electrical jobs. The graph in Figure 2 shows the placement record of Mont Pleasant since 1934.

Boys who have gone on to engineering schools after graduation from the Mont Pleasant High School course have been particularly enthusiastic, saying that the practical training they received not only enabled them to maintain better records in college, but also was of great benefit in securing part-time employment of a character helpful in their further education.

The boys seem to be impressed with the fact that a clear understanding of the basic sciences and how they apply to our modern way of living is as much an element of culture as a knowledge of Greek and Latin used to be. At any rate, the engineer need not apologize for his calling, as it has contributed as much to the comforts and progress of man as has any other field of endeavor.

We feel this plan provides a splendid fundamental training for life, with both college and industrial employment open to the students. In many instances, it has made it possible for a boy to earn his own college education, when otherwise it would have been impossible for him to attend. This industrial experience helps him to appreciate more fully the need of advanced engineering training. He, therefore, goes into college with an attitude that makes him a leader. Our aim is to develop the whole boy and thereby build useful citizens.

Figure 4. A corner of the machine shop with boys at work

Photoelectric System Controls Traffic in Continental Divide Tunnel

A photoelectric block-signal system controls the traffic of men and materials which constantly flows in both directions in the 13-mile-long $50,000,000 Continental Divide Tunnel now being drilled between Grand Lake and Estes Park, Colo. Part of the Colorado–Big Thompson project of the United States Bureau of Reclamation, this tunnel will bring water from the western slope of the Continental Divide to the eastern side, where it will be used for irrigation and the production of electric power.

The trains in the tunnel travel on a 24-inch-gauge single track with passing tracks at convenient intervals. The signal system indicates to train crews the presence of a train in the next section of the tunnel. This prevents accidents and reduces waiting time at passing tracks.

Because the accumulation of water and dirt around switches connected to the rails would impair the efficiency of the signal system and thus cause added expense and delay, and because electric currents in the rails might cause premature ignition of blasting charges, a signal system without mechanical or electrical switches connected to the rails was required. The track, therefore, was divided into blocks of about 6,000 feet, each block ending wherever a turnout occurs for passing. At the beginning and end of each block were placed two photoelectric relays spaced about 30 feet apart, which control the operation of red and green signal lights in that block. Each relay has two light sources located across the track and spaced about 15 feet apart, so that only a locomotive or train can operate the lights.

All green lights are on when the track in a block is clear. When a train or locomotive enters the block and interrupts the light beams directed on the first relay, there is no reaction, since this relay controls the already lighted green lights. When the light beams directed on the second relay are interrupted, however, the green lights are extinguished, and the red lights turned on. The reverse happens when the train emerges from the other end of the block.

This is said to be the longest tunnel in the world protected by photoelectric block signals. The signal system was designed by the General Electric Company.

Substitute Materials in War-Plant Lighting

EDWIN D. TILLSON

IT IS GENERALLY known that a limitation order is being prepared by the War Production Board prohibiting the use of steel for reflectors on fluorescent lighting equipment. The order is being prepared with the co-operation of leaders in the lighting-equipment industry. Without waiting for such an order, many manufacturers have been actively at work on the problem of substitutes, and a few are already in production.

It has been anticipated that the Government will spread the fabrication of war materials over a great number of existing manufacturing premises. Press statements by Government spokesmen in recent months stress the advantages of this program as a move to conserve critical materials required for new building construction and to save the time required to build new defense plants.

To conserve critical materials which would be necessary to build new plants and to save the time required for construction, existing manufacturing plants are being pressed into service for war production. Many of these plants have inadequate lighting facilities. This article suggests that present lighting sources in such plants be supplemented by placing at strategic working points high-intensity fluorescent local lighting with light-hoods or reflectors. These reflectors, no longer made of steel because of wartime restriction, are now being formed successfully from fibrous materials.

INADEQUATE LIGHT IN WAR-PRODUCTION PLANTS

Observation of typical manufacturing plants, many of them built or added to over a period of 50 years, discloses that their wiring and lighting provisions are extremely meager—possibly sufficient from the owners' standpoint for peacetime production during daylight hours, but sadly deficient from the standpoint of workers' efficiency in extensive war production on a three-shift basis.

The typical scene is overhead general lighting from widely spaced fixtures that furnish from 2 to 5 foot-candles, supplemented by local lighting at or near the eyes of the worker, often with exposed or partly exposed lamps that furnish from 15 to 40 foot-candles of illumination over a small area, along with deep shadows, and intrinsic and reflected glare. It is believed that there is not sufficient branch-circuit copper in these places to permit good overhead lighting of 35 to 50 foot-candles, such as we find in all the new defense plants. Neither is the copper available from the outside.

THE LIGHT-HOOD

As viewed by the Utilities Research Commission, an organization sponsored by the four power companies in the Greater Chicago area, the only alternative is to leave the overhead lighting about as is and obtain high-quality, high-intensity fluorescent local lighting at and surrounding all critical working points. The Commission proposes for this purpose, light-hoods (Figure 1) of inexpensive construction, designed for quick installation with a minimum of sheet-steel, pipe, and wire. It was in the development of these light-hoods, or war-hoods as they are also called that the Utilities Research Commission uncovered interesting data on fibrous products.

The conception of light-hoods is not new. They have been successfully and widely used since they were demonstrated by a Chicago group under the chairmanship of Professor H. B. Dates of the Illuminating Engineering Society. This was some eight years ago.

The advent of the fluorescent lamp has revived the interest in light-hoods for the reason that this lamp removes about the only objection there is to the use of the hoods with incandescent lamps, namely, the long-wave radiant energy which, at low mountings, caused considerable discomfort at certain times of the year.

The important point is that light-hoods obviate nearly all of the disadvantages of localized lighting. That is, they are characterized by a very low surface brightness—1 to 1.5 candle power per square inch—and they constitute a large, projected light-source area—16 square feet in the case of URC hoods as compared with from 1/4 to 1/2 square foot for the usual local light source. Light-hoods may be constructed to furnish anywhere from 40 to 50 foot-candles over an area of 100 square feet with a wattage slightly under 200, including auxiliaries. The light is practically shadowless and comparable with the best natural light as obtained from north exposure.

NONMETAL LIGHT-HOODS

Manifestly such large hoods could not be made of steel at this time. Experiments were first made with 1/16-inch slot insulation (Figure 2) which is well known to electrical engineers, having been used for the lining of slots in rotors and stators for many years.

Flat material is ideal from a manufacturing, shipping, and replacement standpoint. It requires no preforming

Essential substance of an address presented at the AIEE summer convention, Chicago, Ill., June 22–26, 1942.

Edwin D. Tillson is a testing engineer with the Commonwealth Edison Company, Chicago, Ill.

Figure 1. A light-hood with reflector of substitute material

and can be delivered flat and sprung into the proper curve by the user. Extensive trials, however, disclosed that even with careful over-all coatings of enamel, baked on, the fiber absorbs moisture. It expands and contracts after installation, causing warps and buckling.

Manufacturers have offered a material 1/8-inch thick similar to Masonite except that it exhibits a hard smooth surface on both sides—hence the designation S2S (Figure 3). This material is not oil-tempered. It contains a limited amount of plasticizer. Unlike tempered Masonite, this material requires no immersion before forming. Heretofore the forming of Masonite, Bentboard, Weatherboard, and Hardboard, has been done by jobbers in several of the larger cities. Where formed fiberboard is used for furniture, show-window trim, and display booths, there almost always has been the opportunity to frame the object with wood battens. Usually it was possible to conceal these battens or to use them in forming part of the design. These wood battens or framing served to hold the edges of the bent fiberboard in alignment. However, in the case of reflector there are two free edges which cannot be so supported.

METHODS OF FORMING FIBROUS LIGHT-HOOD

The common method of forming fiberboard has been to place the material between a stationary pipe and a concave shoe or platen. As the material is squeezed between the two, steam is applied to the interior of the pipe raising its temperature to approximately 500 degrees Fahrenheit. The mechanical pressure is obtained through hydraulic jacks. The pipe is kept in alignment by struts from overhead with turnbuckles for final adjustment. The method is illustrated in Figure 4.

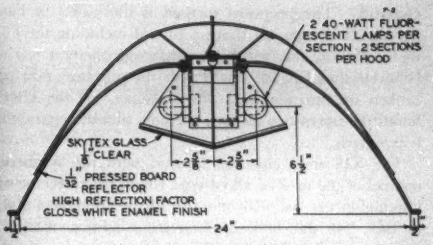

2 40-WATT FLUORESCENT LAMPS PER SECTION 2 SECTIONS PER HOOD
SKYTEX GLASS 1/8" CLEAR
2 5/8"
2 5/8"
6 1/2"
1/32" PRESSED BOARD REFLECTOR HIGH REFLECTION FACTOR GLOSS WHITE ENAMEL FINISH
24"

Figure 2. Cross section of a light-hood using slot insulation of hard fiber for reflector

Suppose that the shape desired is the typical Reflector Lamp Manufacturers contour as shown in Figure 4. The forming is done as at *A;* then the material is unclamped and shifted to point *B* where the operation is repeated. However, this type of operation is neither fast enough nor otherwise suitable for fixture reflectors. As might be surmised, the internal structure of the material is altered by the pressure and temperatures applied. That is, it is altered over the area in contact with the pipe and the shoe. The structure of the material outside of the areas *A* and *B* is not changed but remains as in the original material as it comes from the mill. The tendency on release from the press is for the flat portions to warp.

It is proposed therefore to build presses for the sole purpose of producing fluorescent-lighting reflectors. These presses will have male and female platens, covering the entire surface of the reflector sheet (Figure 5). In this way all portions of the sheet will be subjected to the same temperature and pressure. Preliminary experiments indicate that although the final reflector may not be absolutely true, it will be commercially acceptable and possibly as free from warp as similar sheet-steel

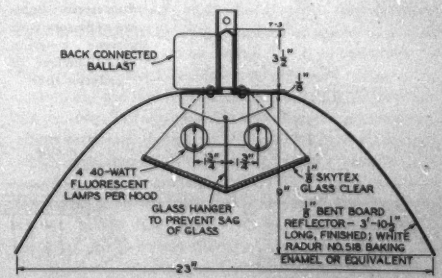

BACK CONNECTED BALLAST
3 1/2"
1/8"
4 40-WATT FLUORESCENT LAMPS PER HOOD
1 3/4"
1 3/4"
1/8" SKYTEX GLASS CLEAR
9"
GLASS HANGER TO PREVENT SAG OF GLASS
1/8" BENT BOARD REFLECTOR— 3'-10 1/2" LONG, FINISHED; WHITE RADUR NO. 518 BAKING ENAMEL OR EQUIVALENT
23"

Figure 3. Detailed cross section of a light-hood showing use of S2S reflector board

contours. The proposed method is illustrated in Figure 2. It is expected that up to and including the 63-inch reflector, this will be a satisfactory method. It is believed that beyond this length the reflector must be broken up into sections. For example, for the URC hoods the use of two sections per side, slightly separated, is expected.

The S2S sheet may be sprayed with the synthetic enamel of the urea or alkyd type which have become so popular in the last year or so for major appliances and, in fact, for the bulk of fluorescent-lighting fixtures. These enamels are baked on at a temperature of approximately 300 degrees Fahrenheit preferably in a radiant drying tunnel. Reflection factors from 83 to 89 per cent are possible with this finish which is also very hard and flexible. It is also both acid- and alkali-resistant.

The S2S board does not fulfill the requirements of the Underwriters' Laboratory as regards flameproofing. For the duration of the war, however, it is expected that where the fiberboard forms one wall of the wiring channel (the bottom), it will be covered with a light-gauge strip of metal and that this will be acceptable. If the entire elimination of steel becomes imminent for fluorescent fixtures, sheet Transite will become a possibility. This is another material familiar to electrical engineers. The manufacturers of the material discourage the idea of forming into channels on account of the time, expense, and priority requirements of the steel dies involved. The URC has made up wiring channels from flat Transite sheet. This is illustrated in Figure 6. The component parts are fastened together using number three flat-head steel wood-screws which cut their own thread. The result is a very neat and workmanlike job. This method of fabrication is one familiar to utility men for oil-switch and pothead barriers.

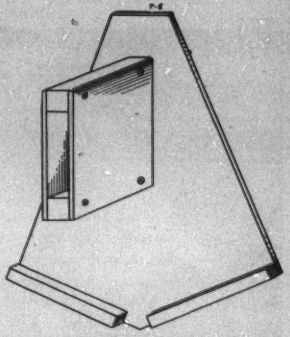


Figure 6. Wiring channel made from flat Transite sheet

The finished reflectors have the appearance of steel and the uninitiated would not observe any difference. It is probable that after the war the use of the substitute will be continued. For large light-hoods, if made of steel, a very heavy gauge is necessary, since when subjected to sudden impact, the steel acquires a permanent crease or deformation which is almost impossible to remove. With fiber this does not occur. The material is highly resilient and very light in weight compared with the steel which it would normally replace. The price is comparable with steel under normal business conditions.

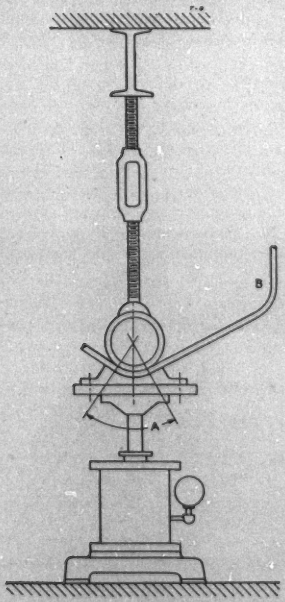
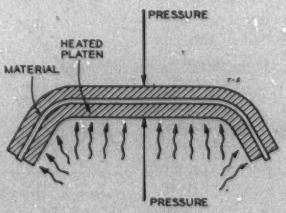


Figure 4 (left). A common method of forming fiberboard between a stationary pipe and a concave platen

Figure 5 (below). A press for forming fluorescent lighting reflectors with platens covering entire surface of reflector sheet



CONCLUSION

There still remains the steel and copper in the fluorescent ballasts and fixture wire. So far as the fixture wire itself is concerned, the amperage for fluorescent fixtures is quite small and in a portion of it, namely, the starter leads, the current is only momentary, so that there has been some experiment with iron wire insulated with plastic sleeving. At present, ballasts without iron and copper do not appear feasible, but it should be remembered that it is extremely difficult, if not impossible, to attain the intensities and quality of light required in war plants with incandescent lamps using the existing circuit capacity. To attain the same results with incandescent lamps undoubtedly involves more iron and copper than are contained in the fluorescent ballasts, or more than would be obtainable under war conditions.

Electrical Concepts at Extremely High Frequencies

SIMON RAMO
ASSOCIATE AIEE

WHEN such fundamental concepts as current and voltage and circuit are to be examined, it should not be concluded that these notions will shortly be tested and liquidated as not applying to the ultrahigh frequencies. But it is admitted that many of these concepts are, generally speaking, carry-overs from static or low-frequency phenomena and that it is "fitting and proper," as well as good engineering, to stop and make certain that our ideas of electricity are broadened and enhanced by our knowledge of what electricity is at the lower frequencies—broadened and enhanced but not handicapped. It is very easy to paint too crude, unsatisfactory pictures of short-wave-length electricity, if we are to limit ourselves to painting with a huge brush intended for long-wave-length pictures.

Some of the characteristics of electricity when the frequency of alternation reaches the range of billions of cycles per second are discussed in relation to the physical pictures of basic electrical concepts, such as current flow along conductors, in tubes, and in circuits which are being evolved by engineers in the high-frequency field. As applied to high-frequency phenomena, some of these concepts now are being modified or broadened in order that more accurate pictures may be obtained.

For support of this point of view, let us look for a moment at one of the most descriptive diagrams (Figure 1) the physicists have yet given us: a plot of the spectrum of electromagnetic phenomena, frequency and wave length of electromagnetic radiation from the power frequencies, through the radio bands for ordinary broadcast radio, frequency modulation, television, past the ultrahighs, and out of the region we call radio waves and into that we call heat waves or rays; then light rays, visible and ultraviolet, and off into electron beams or cathode rays, X-rays, and cosmic rays. All are electromagnetic phenomena, cousins differing in at least one basic way: frequency or wave length, frequencies from a few to well over a few trillion alternations per second, wave lengths from over a billion meters to a billionth of a meter.

Now, the part of the spectrum with which we are presently concerned is in the range of wave lengths described in centimeters or in the range of frequencies described in billions of cycles per second—a region which, except for Hertz' brilliant impudence in producing sparks near there as the first experiment in radio, long before the intervening region had been gone over at all, we have reached by advancing steadily upward in frequency from the left. Notice how far the centimeter-wave region is from the power frequencies and how appreciably close it is to the heat region and even the light region. In fact, the distance to the ordinary radiobroadcast bands and to the heat and light waves is of the same order of magnitude. As one looks at this diagram, he cannot help wondering how far we can continue to go towards higher frequencies before we cease talking about those ultrahigh frequencies as radio waves and start calling them heat or light waves. Better yet, perhaps some new name is needed to show that these waves are separated from radiobroadcast and heat waves just as heat is separated from light. Also it might be expected that if concepts to help in understanding and describing these centimeter waves were going to be borrowed, they would be borrowed from the waves that are shorter as well as those that are longer.

Suppose we had previously worked with light and heat waves exclusively and gradually found means to make those waves longer until we found ourselves, let us imagine, into the really long wave lengths at the extreme left. In light one speaks about the index of refraction, prisms, and lenses and in heat one thinks about the temperature of the source, and black-body radiation. Suppose we had to wait to have it occur to us that such things as motors and power lines and broadcasting stations might be practical realizations, with our thinking governed entirely by concepts like focal length, virtual images, probably some low-frequency extension of Plank's Radiation Law, and a definition of entropy.

Actually the situation is not so radically different in the centimeter-wave region as this exaggerated reasoning might lead one to believe. There are many concepts which need modification when electricity alternates at extremely high frequencies, but in most cases the reason why they need modification is because they were too narrow in the first place. If the broader concept is used, it usually covers the whole frequency range. At the lower frequencies the broad concepts may appear clumsy and so we are satisfied with the narrow ones;

Essential substance of a conference paper presented at the AIEE North Eastern District meeting, Schenectady, N. Y., April 29–May 1, 1942.

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but, if we fail to broaden the base, we may find our physical pictures inadequate, if not entirely erroneous and misleading when applied to the ultrahigh frequencies. With this viewpoint in mind, a description of the presently developing physical pictures of electrical concepts in the centimeter-wave region will be attempted.

CURRENT FLOW IN CONDUCTORS

Current flow in conductors, perhaps the most fundamental of all concepts in electrical engineering, is pictured in as simple a fashion by the microwave engineer as by one who works exclusively with direct current, but the role of conductor-current flow in an electrical system undergoes significant changes. Skin effect reaches its ultimate in the centimeter-wave region and currents are no longer thought of as flowing in, or being contained in conductors. Currents and charges flow and rest on conductor surfaces or at least they come so close to doing so that conductor-current flow becomes a surface phenomenon.

Now this has a very important effect upon the engineer's thinking. Almost the first thing one wants to know about centimeter waves is where they are. If nothing really goes on inside conductors, if only conductor surfaces take part in the action, then the conductors become simply boundaries enclosing regions in which the centimeter waves really do their propagating and existing. This does not mean that the current concept has less meaning or is less useful; it is only that conductor-current flow must now more often share the limelight in

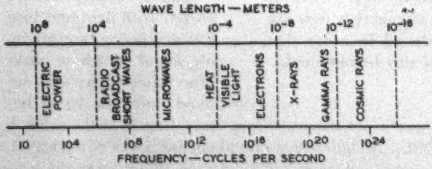

Figure 1. The spectrum of electromagnetic phenomena

a problem with electric and magnetic fields. This tends to make electric effects in the centimeter-wave region ally closely with light waves which we usually consider as passing through a medium with the boundaries being either reflectors or absorbers, but definitely the boundaries of the problem, not the central core. Light, we ordinarily think of as a phenomenon that takes place in a medium which will transmit light, not as something that takes place along mirrors or along other boundary surfaces.

CURRENT FLOW IN VACUUM TUBES

It may seem irrelevant to consider concepts that have to do with a device, such as an electron tube, but it is of prime importance to appreciate not only that the electron tube is the machinery of the centimeter-wave engineer, but that tubes and circuits are so closely interrelated that any concept of current flow is poor unless it correctly pictures centimeter-wave current flow from conductors into electron beams and back into conductors again.

Perhaps the most important piece of concept broadening that applies to current flow in vacuum tubes at ultrahigh frequencies is the rejection of the notion, usually satisfactory for the lower frequencies, that instantaneous current flow between electrodes results from the instantaneous arrival of electrons to one electrode, the electrons having come from the other electrode with no time required for transit. With this picture, an electrode takes no current unless it collects electrons. A negatively biased electrode would thus take no current at any instant, if it collects no electrons.

A safe and correct viewpoint is to consider the current in an electron tube as arising from induction in the external circuit because of the presence and motion of charges in the space between electrodes. The time when the electron is finally collected is not the time when current flows; as a matter of fact, that is the time when current due to that electron ceases to flow. When the electron is almost at the electrode, it is so close to that electrode compared to its distance to others, that that close conductor will have received almost all of the lines of electric field flux emanating from the electron. Whatever charge had to come up through the external circuit to furnish an equal but opposite charge on the electrode, has reached its maximum value; when the electron lands on the electrode it neutralizes that charge and completes the picture.

If there is a continuous stream of electrons coming from, say, a cathode to an anode, then, as each electron moves across, it transfers the matching electric charge, present on the face of the electrodes, from the cathode to the anode through the external circuit. A continuous process, a steady flow of electrons, means then that the current flowing in the circuit is equal to the number of electrons arriving per second at the plate times the electronic charge. In this case, the two concepts agree: Current flow in a vacuum tube may be regarded as due to the instantaneous arrival density of electrons to the electrode, or it may be regarded as a movement through the external circuit of the induced charges on the electrode, occasioned by the electrons' presence and motion. Whichever way one looks at it, one gets the same answer. But in the absence of this regularity, there is nothing in the rules that says that the number of electrons leaving the cathode at any instant must equal the number of electrons arriving at the plate at that same instant. Particularly is this so if the frequency is so high that the time taken by electrons to move across is comparable with the time for a complete electrical cycle.

The centimeter-wave engineer, when he thinks of current flow through an electron tube, cannot overlook

the fact that that current flow is due to a motion of charges, and that it is an integrated effect of all the induced current due to all the charges with which he must deal. The chief tool, the chief machine of the engineer in the centimeter-wave region, the vacuum tube, is not universally looked upon as a switch or an impedance which can be varied by variation of the various biasing voltages on the electrodes. Instead, the centimeter-wave engineer finds himself thinking about electron paths, electron velocities, transit time and induced currents, and movements of waves of space charge.

CIRCUITS

It may be said that circuits in the usual sense—current around a loop constant in magnitude and phase, instantaneous propagation of the fields due to the currents and charges—rarely are to be found at frequencies of billions of cycles per second. In a few centimeters, a distance comparable to wave length, the current will likely have changed enough to reverse. Many circuits are big enough to have one or more reversals of current around the circuit path and that means piling up of charges periodically along the length of the circuit. All in all, it is better to look at the circuits as transmission lines.

Because the circuits are large compared with the wave length, the amount of energy is proportionately large that refuses to be guided by the conductors to dissipate itself within the system, but prefers to continue on through space on its own, without benefit of guidance by the conductors when it has felt the freedom of propagating as transmission-line waves for a certain distance. A major problem of the centimeter-wave engineer in many of the systems which he designs is to minimize that radiation. The centimeter-wave engineer, in other words, has a problem in insulation. Here we see centimeter waves acting a good deal like heat as well as light.

If radiation is so extreme, if the leakage of energy of centimeter waves from these circuits is so high, then how do we design circuits at these frequencies so as to contain the energy? The answer is found in the fact that centimeter waves will not penetrate metal. If one builds a circuit, it should be built so that the current flow around that circuit is self-enclosing. Figure 2 shows what is meant. Here we see a capacitance shunted by an inductance, an example of the most common impedance in radio engineering, a parallel-tuned circuit, the inductance tuning the capacitance to resonance and yielding a very high impedance. We still need high impedances in the centimeter-wave frequency band but we want no uncalled-for radiation. So, we take again two plates for the capacitance, closing those plates first by a one-turn inductance. Then, to make it self-shielding, we apply more one-turn inductances all around the capacitance plates and the completely closed box results. One may think of the walls as made up of many small cross-section inductance bands in parallel. The capacitance, consisting of the two plates, is closed by the surface on which current flows and it is closed all the way around. All electromagnetic effects, all manifestations of the presence of centimeter waves are confined, practically speaking, to the inside of the completely closed cavity.

These resonant cavities are used as filters, input and output impedances of tubes, and, in general, may be said to be as common in the microwave region as the

Figure 2. A capacitance shunted by an inductance

simple lumped-resonant circuits are in the broadcast band. It can readily be appreciated then that the picture of a circuit which the microwave engineer comes to have includes as paramount features such considerations as the various modes of current and electric- and magnetic-field distributions inside of closed regions, and the dimensions of those cavities with respect to wave length. Just as much as the power engineer finds his thoughts of circuits filled with wye and delta connections, so the centimeter-wave engineer thinks of standing-wave patterns in enclosed regions.

VOLTAGE DIFFERENCES

The notion that a conductor is always an equipotential surface, true for electrostatics, is of course totally inapplicable as a general law at frequencies for which currents, charges, and fields actually reverse themselves in a space difference measured in centimeters. For two points on a piece of metal a very short distance apart, it might seem that this law is still valid. But this is not always the case. The common use of self-enclosing conducting systems, such as resonant cavities, very often brings about circumstances in which this persistent but erroneous concept is difficult to reject when one's ideas of voltage difference have become inbred at the lower frequencies. Since centimeter waves will fail to penetrate metal to any appreciable degree, it often happens that very high currents flow on one side of a thin piece of metal, thin compared to wave length but thick compared to the depth of penetration of the current, with resulting high fields and charges in the metal's vicinity on that side, while on the other side, the region is field-free and the surface is free from charges and currents.

For example, the box of Figure 2, if stimulated by a generator on the inside, which charges the top and bottom of the box against each other with accompanying high electric field vertically down the center of the box, may be said with care to possess a voltage difference between top and bottom, where the voltage difference is defined as the integral of the field strength. But an observer, even a very conscientious one, seeking to measure that

voltage difference between top and bottom from outside the box, will obtain no appreciable reading if the metal of the box has any appreciable thickness. The inside and outside of the metal in this particular case cannot be properly regarded, in other words, as at the "same potential" even though the thickness of the metal is very small compared to wave length. Centimeter-wave engineers, although accustomed to making good use of the conventional notions of voltage difference, are becoming equally accustomed to regarding the practical inability of centimeter waves to penetrate metal, a more fundamental concept as a guide to proper use of the less fundamental conventional voltage-difference concept.

TRANSMISSION LINES

Radiation loss possibilities exercise the same controlling action on the choice of transmission lines for centimeter-wave guiding as they do on the choice of circuits. A practical transmission line to the centimeter-wave engineer usually means a self-enclosing system. A coaxial line is one example. A more interesting type of transmission system that is a better example of how centimeter-wave work is expanding our ideas is the so-called wave guide. This term usually implies a single hollow conductor down the inside of which the energy flows. To the microwave engineer, it represents a practical means of guided-energy transmission which, for its understanding and design, requires emphasis upon the relation between cross-sectional dimensions and wave length not previously a factor of much importance in the transmission line picture. If the frequency is slightly below a certain value, any given hollow tube will very highly attenuate the waves passing down it; if slightly higher than the critical value, the wave guide will become a relatively low-loss transmission system.

RADIATION

With wave lengths in the centimeter range, it becomes possible to borrow concepts from light and sound and as with light and sound to attain beaming effects with reflectors and horns. There is no true broadening of concept here; it is simply that these devices work best if the number of wave lengths across the opening of the horn is high, and such a condition would require enormously large structures at the lower frequencies.

Of greater interest is something that is taking place in the centimeter-wave engineer's pictures of the electromagnetics underlying circuits, transmission lines, and radiators as a result, no doubt, of the greater role radiation plays in the two former classes of electrical systems. It is being appreciated that the radiation of electromagnetic energy is not an entirely distinct phenomenon from the guiding of such energy around a circuit or along a transmission line.

All three classes are properly being thought of as guides of a sort, manifestations of the same phenomena, differing only in the relative magnitudes of their common characteristics. If the conducting and dielectric boundaries are so situated around the source that the energy is mainly contained and dissipated in a relatively small region, then the system is usually thought of as a circuit. If the boundary shapes are such that the energy is guided along a somewhat longer path and absorbed or reflected at the termination with, again, the losses to the surroundings relatively small, then it is probably best termed a transmission-line system, or guide. If the boundaries are such as to draw the energy out of the source and encourage it to continue on through free space with little or no further guidance and with relatively little reflected back to the source, then it is an efficient radiator or antenna.

Experimental vacuum tubes developed by Bell Telephone Laboratories to extend the frequency range of the negative-grid type tube. The smallest, about 1 3/4 inches in diameter, can be used as an oscillator at wave lengths as short as 16 centimeters

The Engineer and the Engineering Method

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DOCTOR Charles Felton Scott, a leading engineer and educator of our time, and a past president of the Institute, once expressed the difficulty of defining the term "engineer" as follows: "Our profession is not fixed; it is changing. Even 'the engineer' is an enigma. The learned director of Engineering Societies' Library told me that after spending hours trying in vain to define the engineer he took solace in agreeing with an English friend, 'an engineer is one who can draw sufficient conclusions from insufficient data.' "[1]

At the centennial celebration in 1924 of the Rensselaer Polytechnic Institute, "the first school now in existence which was established in any English-speaking country primarily for the purpose of teaching science and engineering"[2] several speakers indicated what, in their opinions, were the distinguishing characteristics of the engineer. Some of these statements follow.

In a time when values need to be clearly defined, the expressions of several eminent engineers on the distinguishing characteristics of the profession are here presented and analyzed.

"This body of men whose work has been the application of the sciences to the control of force and the production of definite things are men who must from the nature of things be trained in precision of thought. To them every step is the quantitative valuation of forces and materials"—Herbert Clark Hoover, then Secretary of Commerce.[2]

"The modern engineer should be less a technician than a man of broad general training, less an expert mechanic, or electrician, or miner, or what not, and more a man thoroughly grounded in pure science, with especial ability to face new problems and to prosecute original investigation"—James Rowland Angell, president of Yale University.[2]

"In the practice of his profession the engineer cannot always be content with the scientific data at his disposal. He must often take the initiative in its production, working in conjunction with the expert mathematician, physicist, chemist, geologist, and even the biologist. To know when and how to utilize the services of experts, scientific or otherwise, is one of the things that should not be overlooked in technical training.

"If the desired material is not available, the possibility of its production must be considered. To know these materials, their characteristics, and how to use them, how to co-operate with experts in the production of a material for a definite purpose, is another essential that must receive earlier attention.

"The engineer or technologist must assume responsibility and guarantee results more than other professional men. The results of his work can generally be measured or tested. Therefore, the things that develop courage in taking responsibility and getting at the facts of a case must be emphasized in his training. He should look at every task with an open mind, with a view to securing information that will enable him, or someone else, to do it better in the future, a producer of knowledge, not alone a consumer, a leader as well as a follower in his profession"—Samuel Wesley Stratton, president of Massachussetts Institute of Technology.[2]

"Canals, bridges, water works, irrigation systems, great architectural structures were built by the ancient Egyptians, Greeks, Romans, Peruvians. The practice of engineering in their day was a matter of practical craft rather than the application of known principles. It is our modern age which has added most to the widening reservoir of known fact and tested theory"—Carl Ewald Grunsky, president of the American Society of Civil Engineers.[2]

The engineer and his profession have been discussed before professional gatherings as well as in the academic world. The chairman of Institution of Electrical Engineers, said in an address delivered at Manchester, England, October 19, 1937: "An engineer is a person who harnesses and utilizes the forces and materials of nature in the service of man. The definition contained in the charter of The Institution of Civil Engineers states that certain persons had formed themselves into a society 'for promoting the acquisition of that species of knowledge which constitutes the profession of civil engineering, being the art of directing the great sources of power in nature for the use and convenience of man.' He must, therefore, be not only a discoverer but also in a sense a craftsman. He combines some of the functions of the scientist with the skill of the mechanician. It is his task to discover the workings of nature and to apply that knowledge to the satisfaction of human desires and the increase of the amenities of life. In a sense he has one foot in the academic world and the other in the world of affairs. He must know not only what is theoretically possible but also what is commercially and economically practicable. He must have close contact with inanimate materials and also with human beings and be capable of co-operation with them."[3]

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The author wishes to express his appreciation to Doctor Eugene W. Pike for help in discussing and formulating this article.

A. M. MacCutcheon, vice-president in charge of engineering, Reliance Electric and Manufacturing Company, Cleveland, Ohio, and AIEE past president, in an address on the selection and training of engineers, delivered before many AIEE Sections, said: "A clear, concise, definite, and comprehensive conception of an engineer is essential. The dictionary definition—'one versed in or practicing any branch of engineering'—does not meet the requirements. Of the definitions submitted, the following was the best: 'An engineer is one who through training, study, and practice successfully adapts and controls the materials and forces of nature to the benefit and advantage of himself, his fellow engineers, and the rest of the human family.' "[4]

Doctor William F. Durand, chairman and later president of the Third World Power Conference held in Washington, D. C., in September 1936, stated in an address delivered before that conference: "The engineer has been defined as one who is concerned with the utilization of the materials and the energies of nature in the service of man. Amplifying, in terms which define his field of activity and which stand in the preamble to the constitution of American Engineering Council: 'Engineering is the science of controlling the forces and of utilizing the materials of nature for the benefit of man, and the art of organizing and directing human activities in connection therewith.' "[5]

Doctor Scott, in a speech already referred to, before the convention of the National Council of State Boards of Engineering Examiners, said: "Engineering is the agency for making the discoveries of science of practical use. It has two aspects—the theoretical and the practical. It is concerned on the one hand with new knowledge and getting it into usable form and testing it by experience. On the other hand is its application to practical use."[1]

Thus, the engineer has to deal with "the application of sciences to the control of force and production of definite things." He must be "trained in precision of thought . . . quantitative valuation of forces and materials" . . . "less a technician than a man of broad general training" . . . "a producer of knowledge." The implication is that the engineer is a scientist, not a craftsman. On the other hand, he must be "not only a discoverer but also in a sense a craftsman," with "one foot in the academic world and the other in the world of affairs." He has a background of "training, study, and practice." His field of activity is described as "the *science* of controlling the forces and of utilizing the materials of nature . . . and the *art* of organizing and directing human activities." His work "has two aspects—the theoretical and practical," and "is concerned with new knowledge . . . getting it into usable form . . . testing it . . . its application to practical use."

The engineer, then, may be defined as a craftsman and a scientist, an economist and an executive. How does he proceed in performing his tasks? Probably the best general description and definition of "engineering method" is given by Gano Dunn, an eminent engineer and Institute past president, president of J. G. White Engineering Corporation, and also president of Cooper Union for Advancement of Science and Art, in the commencement address delivered at the 70th graduation exercises of the Massachusetts Institute of Technology, Cambridge, June 8, 1937.

"It is not *what* the engineer does, but *how* he does it! Not what the engineer's occupation is, but the intellectual processes by which he attacks that occupation.

"In other words, the *method* of engineers, rather than their *occupation*, is the characteristic of the engineering profession. Method is the common denominator of all engineers. While the subject matter of engineering unquestionably will continue to change in the future, not so with the method of engineering. It is certain that the engineer of the future will be using the present method 150 years hence, even if no prescience is capable of forecasting to what occupations that method will be applied.

"What is this remarkable method that has changed the nature of the world? As is well known, it is the method of science—that process of reasoning based upon observed data and working hypothesis which, by inductive and deductive procedure and experiment, arrives at new knowledge.

"It must be pointed out that, except where their qualities are combined, the engineer and the scientist are not the same person, however much they use the same method. Their objectives are different. Many attempts have been made to define engineering, and engineers do not agree on any one definition; but a definition I worked out some years ago seems to stand the test of criticism and of perspective. It is as follows: *Engineering is the art of the economic application of science to social purposes.*

"Being an art, engineering thrives on repetition. It develops skill and it develops style. The second and third power plants that an engineer builds are likely to be better than the first, although there may not have been introduced a single new principle. The scientist, however, shuts his mind as far as possible to all human prejudice and influence of feeling, save only for the divine fire of that imagination which creates the working hypothesis; and he learns how to discern truth and new knowledge in a study of the order of nature.

"The engineer, by the same intellectual processes as the scientist, applies that new knowledge to social service. The essential difference between the scientist and the engineer lies in the economic involvement of the engineer's work. In this hot crucible of the economic test all that the engineer does must be tried. To repeat an old saying, an engineer is a man who can do with one dollar what any fool can do with two; and it is in his economic involvement that the engineer can rise to some of his greatest powers. . . .

"If the key to the scientist is thought, the key to the

engineer is action. Value and utility are the engineer's criteria, rather than truth, which is the criterion of science."[6]

A more specific practical description is offered by Alex D. Bailey, chief operating engineer of the Commonwealth Edison Company, and president of the board of Trustees of Lewis Institute, Chicago, Ill.:

"They brought to the job the ability to analyze the performance of equipment as it had never been done before. They knew how to attack and to solve the technical problems which increased in number and detail. They knew the value of exact information and maintenance of proper records and from these developed exact control of detailed processes; and as a result of this detailed information and the study of operating performance and results, improvements in design were stimulated. Each improvement in turn brought new problems and opened new avenues for further improvements. This was followed by improved control of manufacturing processes with improved products, lower costs, and less arduous labor on the part of the personnel."[7]

According to Doctor Dunn, the engineering method is a method of science. Yet "engineering is the *art* of economic application of science to social purposes." But can the use of methods of science, subject to economic considerations, be regarded as an art? How is this art distinguished from applied science? Is there not a fundamental distinction between the methods of pure and applied science, and the engineering method?

Such distinction seems indicated in the description of the engineer's work as given by Mr. Bailey. It can be clarified if the underlying processes of the scientific and of the engineering endeavor are grouped under two headings:

1. The choice or assignment of problem
2. The method of solution

Pure science has a free choice of any problem in human experience. Its method of approach consists of the analysis of the particular phenomena involved and of their relationships, followed by the synthesis of the similarities into generalizations, or predictions of future behavior.[8]

Engineering, on the other hand, has to deal with problems which are assigned to it and strictly circumscribed. The engineering approach begins with the analysis of the problem in terms of applicable scientific generalizations. Pure science supplies to engineering the generalizations in terms of which this analysis must be made; engineering may depend upon science for a critical evaluation of their application. This critical evaluation may lead to the development of new generalizations useful in further analysis. The engineering analysis in general scientific terms is followed by the process of synthesis of the particular solution into which must enter economic and social considerations as well as scientific considerations. While the scientific analysis and synthesis lead from the particular to the general, the processes used by engineering lead from the general to the particular. Thus, between science and engineering there appears to be a real inversion of method.

The search for new generalizations required to supply deficiencies uncovered in engineering development constitutes the work of applied science. Thus applied science differs from pure science and resembles engineering in that its choice of problems is not free. Its problems originate from the requirements of the engineering synthesis and are circumscribed by the same economic and social considerations which enter into that synthesis. Applied science differs from engineering and resembles pure science in its method of solution, namely, the synthesis of the generalizations on the basis of the analysis of the particular phenomena.

The economic and social considerations that enter into the engineering synthesis call for a solution in which the elements of cost—labor, capital equipment, space, and time—are so proportioned as to approach the marginal utilization of each. For instance, under a social order in which the value of labor is high in relation to the other factors, engineering will resort to the standardization of materials which permits mass production of a limited number of stock items in place of individualized production of specially designed units; standardization and simplification of methods which permit the use of unskilled or semiskilled labor in repetitive operations on highly specialized equipment to produce at low cost what only the highest skill could achieve at a much higher cost with the methods of individual production. Where time is of value, it will develop methods and schedules, synchronizing various operations on various parts of the project in a manner to expedite its completion. Where labor is plentiful and cheap, and time is of no essence, the greatest economy in the use of material and space may call for individual design and production of each unit in successive operations. Thus, a given problem, analyzed in terms of the applicable scientific generalizations, will call for different engineering solutions, each of which will appear as a compromise between the requirements of the problem and the given set of economic and social relationships. The process or the method followed in obtaining such a solution can be called the *engineering method*.

The engineering method can be defined as the art of formulating the solution of an assigned specific problem in terms of the most effective compromise between requirements and costs, using the generalizations, methods, devices, and materials which have been developed by scientific research, adapting them to the existing circumstances, and pointing out the direction of further research needed to develop new generalizations, methods, devices, or materials which would help in formulating a better and more economical solution of the problem. This method can be applied to all fields of human endeavor.

Quoting again, this time from President Karl T. Compton of Massachusetts Institute of Technology, "Our engineering philosophy, with its fusion of the scientific method with practical application, is one of the greatest syntheses of the human mind. . . . By the effectiveness of its method, engineering has won field after field, giving us new respect for mind, and greater power over matter and the unknown. . . .

"If the engineer is to bring his influence to bear on broad public questions he must approach them, not with technical arrogance, but with sympathetic understanding. If he is to counsel the people he must gain the confidence of the people, and this confidence is obtained by placing ministry to the public above all other considerations. This concept of ministering to the public welfare, which is the concept underlying the professional attitude, is the remaining principle that needs to be fully synthesized with other elements that have been combined to form the engineering philosophy . . . if we are to be a true profession we must embrace this third dimension of social responsibility and public service."[9]

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Powder Metallurgy

F. C. KELLEY

Modern powder metallurgy has two principal uses: the cheap and efficient mass production of machine parts that do not require high strength, and the creation of alloys with special properties. Both uses are described and the development of the process is reviewed.

THE ART of forming metallic articles from metal powders represents the earliest form of metallurgy. The Egyptians produced iron implements as early as 3000 B.C., long before the development of furnaces for melting purposes. The process at that time consisted of heating the iron-oxide ore in a charcoal fire with the aid of a bellows, to reduce it to metallic sponge iron. While still hot, it was hammered into the desired shape. Photomicrographs of such implements have been taken by H. C. H. Carpenter and J. M. Robertson, whose findings were published in 1930 in the *Journal* of the Iron and Steel Institute, pages 121, 417–48. Some of the implements were quite free from slag inclusions and compared favorably with modern products made by melting.

Long before the discovery of America, the natives of Ecuador used gold and silver, which form a low-melting-point alloy, to bind together particles of platinum. Platinum was produced by powder metallurgy in Europe during the 18th century. Wollaston is credited with being the first to use a press to form powder into a compact before sintering. He kept this part of his process secret until just before his death.

The developments of the last 30 years in powder metallurgy have kept pace with the tremendous accumulation of scientific knowledge that has contributed so much to raising our standards of living during that period. The outstanding contribution in this field was the invention of ductile tungsten by Doctor W. D. Coolidge of the research laboratory of General Electric Company, Schenectady, N. Y. Tungsten, having one of the highest melting points known, could not be melted, cast, and worked, as can iron or steel. There were no furnaces or ceramic materials which could be used in such processes. In Doctor Coolidge's new method, tungstic oxide was reduced in hydrogen to obtain pure tungsten powder. The powder was pressed at room temperature into bars, but after pressing, the bars could not be handled without danger of breaking. They therefore were given a preliminary sinter at about 1300°C after which they were quite strong. They were then given a high-temperature sintering treatment, just below the melting point, in a hydrogen treating bottle where

Essential substance of a talk delivered before the Engineering Society of Detroit, Detroit, Mich., October 10, 1941.

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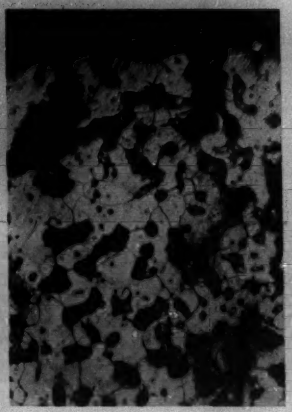
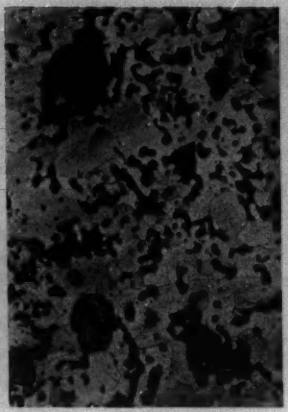


(a)



(b)

Figure 1. Structure in a pinion-gear tooth (a) at the outer edge, parallel to axis; (b) in the body of the tooth

Composition (per cent): carbon 0.08, manganese 0.25, phosphorus 1.39, sulphur 0.024, silicon 0.10, titanium 0.02, vanadium 0.12, aluminum 0.10, nickel nil, remainder iron

Figure 2. Structure of a sample of sintered iron

the current was passed directly through the bar. The sintered bars were then heat-treated in a hydrogen furnace to a white heat, swaged, and finally drawn through diamond dies to be formed into wire. This fine wire was ductile and had great strength. This process is used to make wire for the tungsten-filament lamps now used (see "The Manufacture of Incandescent Mazda Lamps," by James D. Hall, *EE, Dec. '41, p. 574–80*).

The next important development was the invention, by E. C. Gilson of the General Electric research laboratory, of a porous bearing material known as Genelite. It was made from the oxides of copper, tin, and sometimes lead or zinc. The oxides were mixed with graphite and heated in a closed container at a low temperature to allow almost complete reduction of the oxides by the graphite, then screened, and pressed into the desired shapes. These compacts were then packed in charcoal to exclude air, and reheated to about 650 degrees centigrade until reduction of the metals was complete and alloying had taken place among them. These sintered compacts were porous, and when used as a bearing material were saturated with oil. They were also used as brushes for electric machines, but for that purpose were not saturated with oil.

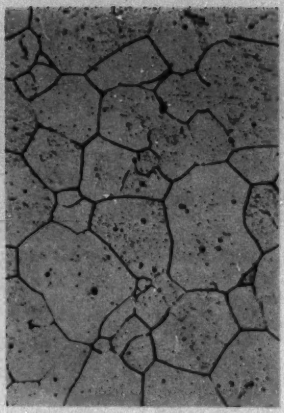
A few years later, N. H. Adams of the same laboratory invented the copper-impregnated tungsten material now used so extensively as an electrode for spot and line welding. This material was made by pressing a bar of tungsten at the desired pressure and sintering it at about 1,300 degrees centigrade in hydrogen. The tungsten then was placed in a graphite boat with copper and heated above the melting point of copper. The capillary attraction of the porous tungsten bar resulted in its complete impregnation with copper. This material had high compressive strength at relatively high temperatures and was also a good conductor of heat and electricity.

The next outstanding development was the invention of cemented tungsten carbide by Heinrich Baumhauer and Karl Schroeter of the Osram Lamp Company, Germany, and the appearance of other mixed-carbide tool materials, such as tungsten carbide–tantalum carbide, tungsten carbide–titanium carbide, and tungsten, tantalum, and titanium carbides bound together with a metal of the iron group, usually cobalt. Balke of the Fansteel Company also made tantalum-carbide tools cemented with nickel. The hardness and toughness of cemented tungsten carbide made it outstanding as a tool material for machining cast iron, steel, Bakelite, hard rubber, and many other materials which cause rapid wear of steel tools.

Several developments in cemented-carbide tool materials of the Carboloy type were made in the General Electric laboratory; namely, hot-pressed cemented carbide, cemented tungsten carbide with substantial amounts of tantalum carbide, and diamond-impregnated cemented carbide for oil-well drills and wheel dressers.

Sintered Alnico, developed by Goodwin H. Howe of the General Electric Research Laboratory, is one of the most recent permanent magnetic materials. It generally is made from aluminum, nickel, cobalt, and iron. Cast Alnico develops a large grain structure, is brittle, and has low impact resistance, but the fine-grained sintered material is strong and has a relatively high resistance to shock.

Figure 3. Structure of sintered electrolytic nickel



(a)

(b)

Figure 4. Sintered nickel made from hydrogen-reduced nickel oxide: (a) showing equiaxed grain structure; (b) at 1,000 magnification, showing precipitate along grain boundaries

Research in the field of powder metallurgy, aimed at reducing costs through the utilization of cheaper materials and the elimination of scrap, has brought about another period of development, this time, on a larger scale. New discoveries may make possible sufficient improvement of certain physical characteristics of a material to justify increased original cost, since longer life, improvement of performance, and other gains result in a final saving.

The automotive industry has used oil-impregnated bronze bearings for years, but more recently Moraine Products and Amplex have produced bearings from sintered-iron compositions. They have also extended their application of these materials to the production of oil-pump gears, door catches, cams, filters, and other devices. The automotive industry is ideal for the application of powder metallurgy, since its product has many small parts that require lubrication. Oil-impregnated bearings can be turned out by automatic machines by the million, sintered in atmosphere-controlled continuous-operating automatic-temperature-controlled furnaces where the raw material goes into one end and the bearing comes out the other, finished except for the oil impregnation. In many cases where tolerances are close, however, a cold-coining operation is required; that is, a resizing by restriking the sintered product in a die, or a final sizing by finish-grinding or machining.

Iron parts to which carbon or graphite have been added may be sintered by a temperature sufficiently high to bring about diffusion of the carbon or graphite into the iron, thus forming steel. Iron may be bound together with copper in the same manner. The parts containing carbon may be heat-treated in the same way as are steel articles made from fused metal that has been cast and worked.

Many applications do not require material with high physical properties, but only lubrication to prevent wear. Some ores from which iron powder is made contain impurities, such as silicates and high phosphorus, which enhance the wear-resisting characteristics. The porosity of the compressed compact is controlled by the amount of pressure applied and the temperature and time of sintering.

One of the outstanding pieces of work in this field is that done on hot-pressed brake drums at Chevrolet Wheel and Axle Company, where steel scrap was made sufficiently fine by grinding that it could be cold-pressed, sintered, and then reheated and hot-pressed into a die. These drums have been tested in actual service and found to be as good as or better than those formed from wrought material. The development of this process naturally depends upon the cost of putting the scrap into such condition that it can be easily formed in a die.

The limitations of the process of powder metallurgy naturally depend upon the availability and cost of material. The material commonly used was Swedish sponge iron, because of its high quality and low cost. That source has now been cut off, but there are many firms in America making powdered iron which can be used for this production if the cost can be reduced to, say, five to ten cents per pound. If the demand for this material is great enough, there seems now to be no question about being able to obtain it at a reasonable price.

Powders when pressed do not flow around corners, as do many plastic materials. On that account, the design of the part being formed is very important. The plungers operate in straight lines, and in order to withdraw the

plunger or eject the compact after forming without breakage of the compact, the design of the die and compact must be correct.

Many automatic machines of the pill-machine type are being used today to turn out small parts, but as the size of the part increases, the machine-tool cost increases greatly. Since the largest presses are not automatic but hand-operated, the cost of production increases with increase in size. Another difficulty encountered with the increase in size is the nonuniform distribution of pressure throughout the compact, which results in uneven shrinkage if the temperature of sintering is sufficiently high. If the temperature is low, the density is not uniform throughout the compact.

Many of the parts made of present materials are lacking in strength, both tensile and impact, for many applications.

The cost of dies for pressing complicated shapes is high, and unless many thousands are made the cost per piece may be prohibitive.

However, millions of small parts, amounting to tons of material, can be turned out on automatic presses, at very low cost. How else could porous bearings, such as those described, be made so cheaply? Bearings made from solid stock are not self-lubricating, have a relatively high machining cost, and represent a considerable loss of material as scrap. In the case of a gear, this loss may be as much as 75 per cent. The loss of material and the cost of machining are saved by using the powder process.

Intricate shapes may be formed with a single stroke of the press and the size maintained by proper sintering or a cold-coining operation after sintering.

Bearings backed by solid steel and filled with oil do not require high strength, and for many applications require no further lubrication throughout the life of the bearing.

SINTERED MATERIALS

Any discussion of powder metallurgy should include some consideration of the factors influencing sintering, as well as of the physical properties of sintered materials.

Illustrating one class of sintered iron used for bearings and gears, Figure 1a represents the structure found in a pinion gear, taken at the outer edge of the tooth and parallel to the axis. It shows considerable porosity and slag inclusions. Figure 1b represents the structure found in the body of the tooth. There is considerably more porosity, which is characteristic of sintered materials.

The strength of a gear tooth under static and dynamic loading was determined by clamping the gear so that a vertical load could be placed on the tooth tangential to the gear periphery, thus loading the tooth in shear, with the effective area that of the root of the tooth. The breaking load was 1,400 pounds, the equivalent of 10,380 pounds per square inch.

For the impact loading, a 1-pound weight was used. It was first dropped from a height of 4 inches and raised 1 inch at a time until rupture occurred. The tooth broke when the weight was dropped from a height of 10 inches. Since the area of the tooth was 0.135 square inch, the weight required to break the tooth was equivalent to 6.2 foot-pounds per square inch.

Experiments have been made to determine the effects of time, temperature, and pressure upon the density of sintered iron, cobalt, and nickel. The powders used in these experiments were all of high purity. The particle size was −200 mesh, with about 50 per cent −325 mesh.

Table I. Composition of Powders Used in Experiments With Density of Sintered Materials

	Iron	Nickel	Cobalt
Silicon	0.013	0.029	0.075
Iron	0.24	0.19	
Hydrogen-sulphide groups	0.19	0.03	
Sulphur	0.024	0.025	0.06
Cobalt	0.41		
Nickel			0.31
Manganese	nil	0.004	0.03
Phosphorus	trace	0.007	0.005

Table IIA. Effect of Pressure on Density of Sintered Iron

Temperature 1,425–1,450 degrees centigrade; time 32 hours

Sample	Pressure (PSI)	Density
1	140,000	7.809
2	120,000	7.824
3	100,000	7.830
4	80,000	7.814
5	60,000	7.836
6	40,000	7.816
7	20,000	7.775

Table IIB. Effect of Temperature on Density of Sintered Iron

Pressure 30 tons per square inch; time 32 hours

Sample	Temperature (C)	Density
1	800	6.96
2	1,000	7.08
3	1,200	7.38
4	1,300	7.433
5	1,350	7.45
6	1,400	7.80
7	1,425–1,450	7.725

Table IIC. Effect of Time on Density of Sintered Iron

Temperature 1,425–1,450 degrees centigrade; pressure 30 tons per square inch

Sample	Time (Hours)	Density
1	1	7.5
2	2	7.55
3	4	7.67
4	8	7.658
5	16	7.77
6	32	7.807
7	64	859 7

Table III. Effect of Pressure on Density of Sintered Nickel

Temperature 1,375–1,400 degrees centigrade; time 32 hours

Sample	Pressure (PSI)	Density
1	140,000	8.722
2	120,000	8.787
3	100,000	8.783
4	80,000	8.763
5	60,000	8.725
6	40,000	8.624
7	20,000	8.480

Table IV. Effect of Pressure on Density of Sintered Cobalt

Temperature 1,375 degrees centigrade; time 32 hours

Sample	Pressure (PSI)	Density
1	140,000	8.66
2	120,000	8.66
3	100,000	8.59
4	80,000	8.7
5	60,000	8.71
6	40,000	8.7
7	20,000	8.72
8	10,000	8.69

Figure 5. Structure of sintered cobalt

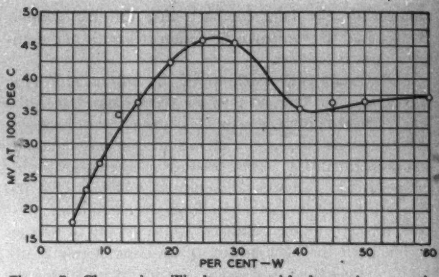


Figure 7. Change in millivolt output with change in composition of nickel-tungsten-nickel thermocouples

Table I shows the composition of the various powders used. Five-gram samples were used for the tests. They were pressed in a steel mold, using a hand-operated hydraulic press so that the pressure could be obtained very accurately. The size of the bars was $^1/_8$ by $^1/_4$ by $1^1/_4$ inches. This small sample was used to secure pressure as nearly uniform as possible throughout the compact.

Sintered Iron. Seven different pressures were used for the iron samples, and they were all sintered on an iron boat, covered lightly with aluminum oxide (Al_2O_3) to prevent sticking, at 1,425 to 1,450 degrees centigrade for 32 hours in hydrogen. The results given in Table IIA show that at this high temperature of sintering, pressures of 30–60 tons per square inch give the highest densities.

Table IIB shows the effect of temperature of sintering where the pressure was 30 tons per square inch and the time was 32 hours. Between 1,350 and 1,400 degrees centigrade there was a marked increase in density. It seems that 32 hours' sintering is not quite long enough to secure the theoretical density of pure iron, or 7.86.

Table IIC shows the effect of time where the pressure was 30 tons per square inch and the temperature 1,425–1,450 degrees centigrade. For this particular iron, 64 hours were required to secure the theoretical density of 7.86.

From the photomicrograph of this sintered iron (Figure 2) the soundness of the compact and the large grain size developed by the long-time sintering can be observed. The small rounded globules are fused silicates.

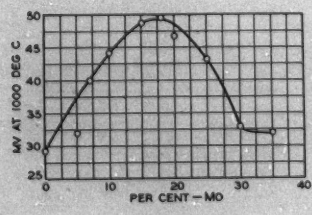


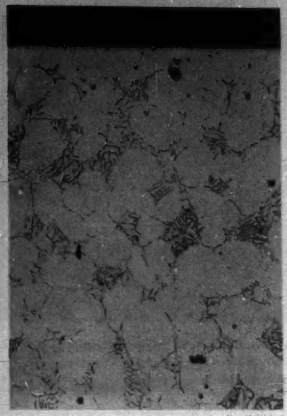
Figure 6. Change in millivolt output with change in composition of nickel-molybdenum-nickel thermocouples

Sintered Nickel. A series of nickel samples was pressed and sintered at 1,375–1,400 degrees centigrade for 32 hours in hydrogen. The results are given in Table III. As with iron, the theoretical density—for nickel, 8.9—was not quite reached in 32 hours. The optimum pressure range seems to be 40–60 tons per square inch. The impurities in this nickel may affect its density also. A photomicrograph (Figure 3) of this material, which is electrolytic nickel, shows the sharp angular grains. Nickel made from hydrogen-reduced nickel oxide and sintered in the same way is shown in Figure 4a. The equiaxed grain structure obtained from this powder may be seen. Figure 4b, a photomicrograph taken at 1,000 magnification, shows a precipitate along the grain boundaries.

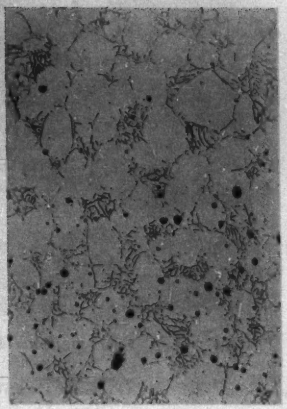
Sintered Cobalt. Cobalt samples pressed and sintered at 1,375 degrees centigrade for 32 hours in hydrogen give the results shown in Table IV. Again there is an optimum pressure range which gives the highest density. This density comes within the range 8.6–8.9. Pure cobalt exists in two different phases, and the density may vary with the amount of each phase present. Since these samples were all sintered together at the same time under the same conditions and made from the same lot of cobalt, this factor may be eliminated as contributing

Table V. Results of Sintering "18–8" Stainless Steel

Sample	Particle Size	Per Cent Shrinkage	Rockwell B Hardness	Per Cent Reduction of Area	Per Cent Elongation	Tensile Strength (PSI)	Density
"18–8" Made from Mixed Powders							
A2	−200	25	65–69	30.5	20	79,250 a 25°C	7.64
A24	−200	24.4	67	17.5	24	19,500 a 1,500°F	7.35
A26	−200	21.8		19.5	30	24,500 to 27,500 at 1,500°F after 25 per cent reduction	7.35
Wulff's "18–8" Powder							
1	−100+200	11.5	62	27	21	54,500	7.886
2	−200+325	10.2	64	56	44	58,300	7.8856
3	−325	7.9	66	66.2	45	58,300	7.895



8(a)



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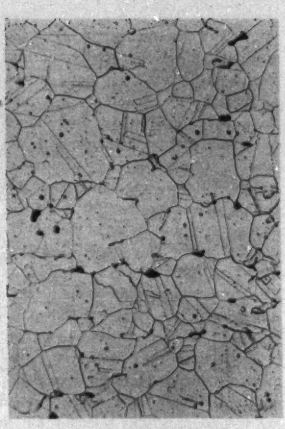
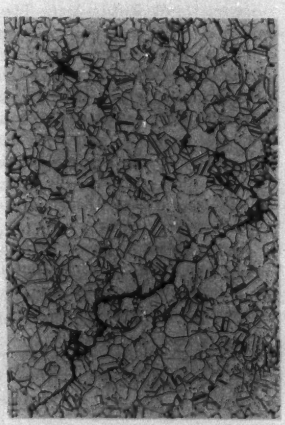


9(a)

Figure 8. Structure in sintered bar of Wulff's "18–8" stainless steel: (a) at surface of bar; (b) at center of bar

to the variation in density. Figure 5 represents the structure of the sintered cobalt.

These results on the sintering of pure metals at temperatures close to their melting points show quite conclusively that sound bars may be obtained from pressed and sintered compacts when sintered for a long enough time. They also indicate that each metal has an optimum pressure at which the highest densities may be obtained. Temperature and time are the most important factors in obtaining sound materials from pressed powders; pressure is the least important. The highest pressures in every case gave densities below those obtained over the optimum pressure range.



9(b)

Figure 9. Structure of Hastelloy B: (a) after sintering; (b) after sintered sample has been reduced one fourth by hot swaging

ALLOYS FROM METAL POWDERS

The highly specialized and scientific work of Doctor W. P. Sykes of the Cleveland Wire Works, on the binary systems of iron-molybdenum, iron-tungsten, nickel-molybdenum, nickel-tungsten, cobalt-tungsten, and other compounds, has all been done with metal powders. It has furnished a means of obtaining the pure materials so essential for accurate work in powder metallurgy.

Iron-Nickel-Cobalt Alloy. An alloy of iron, nickel, and cobalt has been produced by the sintering process, that has all the physical characteristics of the same material made by melting. The chief characteristic of this alloy is that it follows very closely the expansion coefficient of certain grades of glass and is stable over a wide temperature range, even extending to liquid-air temperatures.

The sintered material has furnished a method for accurately controlling the composition and expansion characteristics, avoiding contamination so often encountered in melting, and eliminating scrap losses. The theorist might say that equilibrium could never be established in such a system. As a matter of fact, we seldom deal with alloys which are in equilibrium, and this alloy is an outstanding example of a material produced from powdered metals which can meet such exacting physical requirements as are demanded of a metal sealed to glass.

Nickel-Molybdenum and Nickel-Tungsten for Thermocouples. The General Electric laboratory has produced nickel-molybdenum and nickel-tungsten alloys by sintering, which, when welded to nickel, produce couples capable of operating in hydrogen furnaces at temperatures up to 1,300 and 1,400 degrees centigrade respectively. Tests on nickel-molybdenum–nickel couples over periods above 3,000 hours at high temperatures have shown that they do not vary more than plus or

minus 5 degrees centigrade from the original calibration. No tests of such long periods have been made on the nickel-tungsten–nickel couples, but there is no reason why they should not give equal performance at 1,300 degrees centigrade for an equal length of time. Figure 6 shows the change in millivolt output with the change in composition of the nickel-molybdenum alloy used against nickel at 1,000 degrees centigrade. The same relationship for the nickel-tungsten–nickel couples is shown in Figure 7. These charts show a rather broad peak on the curves, where the millivolt output changes very little with a relatively large change in compositions. These are the compositions selected for duplication of millivolt-temperature characteristics.

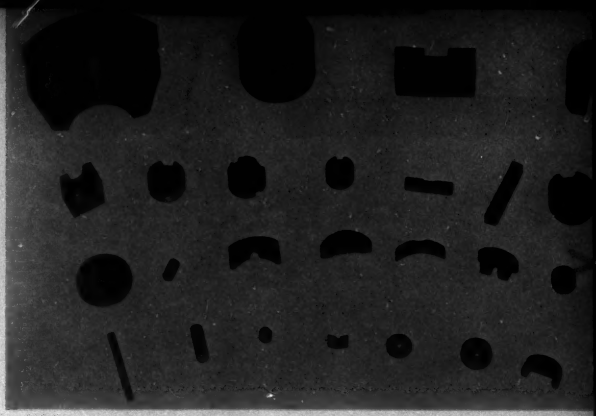


Figure 10. Sintered Alnico magnets of various shapes and sizes

Sintered "18–8" Stainless Steel. The sintering of "18–8" stainless steel (74 per cent iron, 18 per cent chrome, 8 per cent nickel) requires an atmosphere with an extremely low partial pressure of both oxygen and water vapor. Pure hydrogen is one of the best mediums for this purpose. It is made by passing the gas through sulphuric acid, over copper in some form heated 6,000 degrees centigrade, and then over phosphoric pentoxide (P_2O_5). When phosphoric pentoxide is used, the partial pressure of water vapor is so low that chromic sesquioxide (Cr_2O_3) may be reduced by it.

The gas cannot be passed into a commercial furnace and maintain this low partial pressure of water vapor. The sintering must be done in a closed iron tube or some tight container provided with only a small leak for renewal of the pure gas atmosphere.

At the General Electric laboratory we have pressed and sintered "18–8" from mixtures of iron, chromium, and nickel powders, and also from powder furnished by Professor John Wulff of Massachusetts Institute of Technology. The latter powder was made by pickling heat-scrap "18–8" in a solution of sulphuric acid and cupric treated sulphate ($H_2SO_4+CuSO_4$). The carbides are attacked at the grain boundaries, leaving the individual crystals of "18–8" behind. The copper is removed and the powder washed and screened to various sizes.

The results of tests made on the mixed powders pressed at 30 tons per square inch and sintered for 32 hours at 1,375 degrees centigrade are shown in Table V. The percentage shrinkage in volume varied from 20 to 25 per cent. The tensile strength at room temperature was 79,250 pounds per square inch, and at 1,500 degrees Fahrenheit it was 19,500 pounds per square inch.

The elongation and reduction of area were not taken at room temperature, but at 1,500 degrees Fahrenheit the elongation was 27 per cent and the reduction of area 20 per cent.

Figures from the Allegheny Ludlum Steel Company give 80,000 pounds per square inch as the ultimate strength with 55 per cent elongation and 65 per cent reduction of area of annealed "18–8."

Table VI. Results of Sintering Hastelloy

Sample No.	Particle Size	Sintering Pressure (PSI)	Sintering Temperature (C)	Sintering Time (Hr)	Per Cent Shrinkage	Temperature of Test	Tensile Strength (PSI)	Tensile Strength After 25 Per Cent Reduction	Per Cent Elongation	Per Cent Reduction of Area	Density	Rockwell B Hardness
Hastelloy From Mixture of Hydrogen-Reduced Molybdenum Oxide, Electrolytic Nickel and Electrolytic Iron												
C28	−200	60,000	1,250	24	10.4	1,500 F		86,000	10.8	13.0		
C29					15.3	Room	87,000		20.0	11.95	8.16	68.0
C30					13.9	Room	85,000		21.0	15.4	8.25	72.3
C31					16.5	1,500 F	43,000		8.0	8.0	8.2	70.7
Hastelloy From Mixture of Hydrogen-Reduced Oxides of Molybdenum, Nickel, and Iron												
C32	−325	60,000	1,250	24	45.0	1,500 F		61,000	5.0	5.5		
C33					46.0	Room	98,60		0.013	6.53	9.2	101.8
C34					45.8	Room	96,20		0.013	6.96	9.2	102.8
C35					47.8	1,500 F	44,00		5.0	4.0	9.26	103.0
Effect of Time on Hastelloy B (99.5 Per Cent Molybdenum Trioxide Plus Nickel and Iron Oxides)												
D8				2	32.6						8.63	94.3
D9				4	46.9						8.6	92.3
D10		60,000	1,250	8	46.6						8.83	89.5
D11				16	48.9						8.92	96.5
D12				24	45.8						9.0	96.0

The powder furnished by Professor Wulff did not press very solid at 30 tons per square inch, and the sharp corners of the pressed bars crumbled on handling. Three different particle sizes were used: −100 plus 200, −200 plus 325, and −325. Bars sintered at 1,375 degrees centigrade for 24 hours in pure hydrogen gave the results shown in Table V.

With a decrease in particle size, the percentage shrinkage in volume decreases. This is exactly the reverse of the result usually obtained with iron powders. The elongation and reduction of area increase with the decrease in particle size. The physical characteristics of sample 1, which had the coarsest particle size (−100 plus 200) are definitely lower than those of samples 2 and 3, which show very little difference. The densities are well within the range 7.86–7.925 given by the Allegheny Ludlum Steel Company for this material.

A photomicrograph of a sintered bar of Wulff's material, taken at the surface of the bar, is shown in Figure 8a; Figure 8b shows the same material taken at the center.

Hastelloy B. This material (65 per cent nickel, 28 per cent molybdenum, 7 per cent iron) has relatively high strength at high temperature. It has been made from electrolytic nickel and iron and hydrogen-reduced molybdenum and also from reagent oxides hydrogen-reduced to give the metals. The particle size in the first case of the electrolytic nickel and iron was −200, with 50 per cent −325. In the second case, the particle size of the hydrogen-reduced metals was −325.

The sintering of these materials was carried out in the purest hydrogen at 1,250 degrees centigrade for 24 hours after pressing at 30 tons per square inch. The results, as given in Table VI, are extremely interesting.

There is great difference in shrinkage between the C28–C31 and the C32–C35 groups of samples. The higher hardness of samples C33 to C35 is typical of hydrogen-reduced metals. The greater strength of samples C33 and C34 is to be expected on account of their higher densities and hardness. Yet after 25 per cent reduction by hot swaging, sample C28 shows as high strength at 1,500 degrees Fahrenheit as samples C29 and C30 do at room temperature; and sample C32 after 25 per cent reduction by hot swaging shows less strength at 1,500 degrees Fahrenheit than does either sample C33 or sample C34 at room temperature. There is little difference in the strengths of the as-sintered samples C31 and C35 at 1,500 degrees Fahrenheit.

The effect of time of sintering on shrinkage, density, and hardness is given by samples D8–D12. The greatest part of the shrinkage occurred in the first four hours, but the density and hardness increased steadily with time. Figure 9a represents the structure of sintered Hastelloy B. Figure 9b represents the same material after 25 per cent reduction by hot swaging. The hot-worked specimen shows very little porosity. The crack in this particular sample occurred only at the very end of the rod. The grain refinement caused by hot swaging is very marked.

Sintered Alnico. This material lends itself to mass production of small parts. It may be presintered and formed from stock material where a few parts are needed, without making a mold, but pressing a shape by a single operation, as was done with the many small magnets shown in Figure 10, is much more economical for quality production.

A comparison of Alnico magnets with equivalent permanent magnets made of other materials is shown in Figure 11.

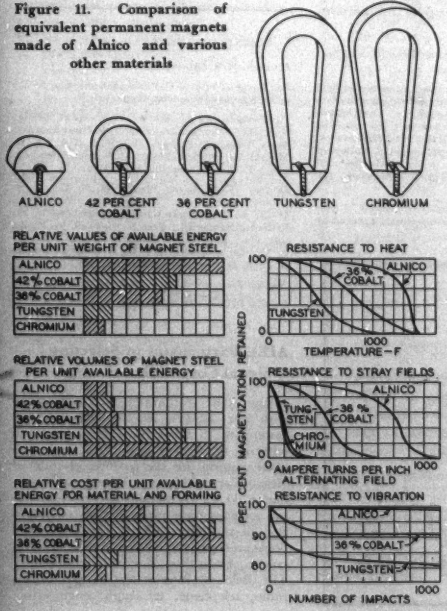


Figure 11. Comparison of equivalent permanent magnets made of Alnico and various other materials

The adequate development of any of the subjects mentioned would require a volume, the author hopes that this article has given those unacquainted with the subject a clearer idea of what powder metallurgy is, and furnished those working in the field with some data on the physical properties of various materials.

INSTITUTE ACTIVITIES

AIEE Board of Directors Meets

The regular meeting of the board of directors of the American Institute of Electrical Engineers was held at Institute headquarters, New York, on August 7, 1942.

Upon recommendation of the standards committee, the board approved for publication as a revised AIEE standard, a revision of AIEE Standard No. 27, "Switchgear Assemblies," submitted by the committee on protective devices.

Recommendations concerning the policies and activities of the Institute under war conditions were submitted by the committee on planning and co-ordination and adopted by the board of directors, as published elsewhere in this issue.

Announcement was made of the appointment by the president of the standing and general committees of the Institute for the administrative year beginning August 1, 1942 (for a complete list of officers and committees for 1942–43, see pages 483–7 of this issue).

As required by the bylaws, the board confirmed the following appointments by the president:

Edison Medal Committee—N. E. Funk, *chairman* for the year 1942–43; F. D. Newbury, D. C. Prince, and W. E. Wickenden *members* for the five-year term beginning August 1, 1942.

T. F. Barton, T. G. LeClair, and K. B. McEachron, elected from the board of directors, *members* for a term of two years beginning August 1, 1942.

Charles LeGeyt Fortescue Fellowship Committee—O. E. Buckley and Ernst Weber *members* for the three-year term beginning August 1, 1942.

Lamme Medal Committee—C. L. Dawes, J. L. Hamilton, and K. B. McEachron *members* for the three-year term beginning August 1, 1942; C. M. Laffoon to serve for the unexpired term, ending July 31, 1943, of R. E. Hellmund, deceased.

As most of the functions of the Institute policy committee come within the scope of the committee on planning and co-ordination as reorganized a few years ago, it was decided to abolish the Institute policy committee, to appoint committees for the consideration of special subjects as occasions arise, and to appoint at this time a special committee on registration of engineers.

Approval was given to dates for District meetings, as follows: North Eastern District, Providence, R. I., April 7–9, 1943; South West District, Kansas City, Mo., April 28–30, 1943.

Representatives of the Institute on other bodies were appointed for the one-year term beginning August 1, 1942. O. W. Eshbach was reappointed a representative on the Engineers' Council for Professional Development for the three-year term beginning in October 1942, and L. W. Chubb was reappointed a representative on the Research Procedure Committee of The Engineering Foundation for the term of one year beginning in October 1942.

The following Local Honorary Secretaries of the Institute were reappointed for the term of two years beginning August 1, 1942:

V. J. F. Brain for Australia
A. S. Garfield for France
V. F. Critchley for Northern India
M. N. Iengar for Southern India
W. Elsdon-Dew for Transvaal

Other matters taken up by the board included the following:

Minutes of the meeting of the board of directors held June 24, 1942, were approved.

A report of a meeting of the board of examiners held July 23, 1942, was presented and the recommendations adopted at that meeting were approved. Upon recommendation of the board of examiners, the following actions were taken: 10 applicants were transferred to the grade of Fellow; 56 applicants were transferred and 14 were elected to the grade of Member; 96 applicants were elected to the grade of Associate; 169 Students were enrolled.

Expenditures in July amounting to $28,018.72 were reported by the finance committee and approved by the board.

NEW MEMBERS

All Institute Members:

Each one of you will shortly receive a letter asking for the names of associates or acquaintances whom you consider qualified for membership in AIEE. Every member must know at least one such individual. Let us have his name! Talk to him yourself! Take him to the next meeting of your Section so that he can see for himself what the Institute has to offer him personally!

John H Pilkington

Chairman, National Membership Committee

Have You Traveled Abroad?

If so, Government Solicits Your Assistance

A letter recently received by National Secretary H. H. Henline from Acting Secretary of Commerce Wayne C. Taylor states that the Government is in need of any specialized or unusual information that might possibly be supplied by AIEE members who have traveled abroad, concerning the commodities used or produced abroad, and also concerning economic, industrial, and social conditions in foreign countries. Casual tourists are excluded, but all who have gone abroad on business trips, or who have resided for a time in foreign countries are earnestly being sought.

All AIEE members who qualify are urged to write at once to Mr. Taylor, U. S. Department of Commerce, Washington, D. C., so that a Department of Commerce inquiry form may be sent to each such member for the brief recording of information concerning foreign countries and cities that have been visited, periods of foreign residence, and business firms or organizations contacted.

Those present were:

President—H. S. Osborne, New York, N. Y.

Past Presidents—David C. Prince, Schenectady, N. Y.; R. W. Sorensen, Pasadena, Calif.

Vice-Presidents—A. G. Dewars, Minneapolis, Minn.; N. S. Hibshman, Bethlehem, Pa.; J. Elmer Housley, Alcoa, Tenn.; C. R. Jones, New York, N. Y.; K. B. McEachron, Pittsfield, Mass.; C. A. Price, Hamilton, Ont.; E. W. Schilling, Bozeman, Mont.

Directors—T. F. Barton, New York, N. Y.; M. S. Coover, Ames, Iowa; M. Eldredge, Washington, D. C.; C. M. Laffoon, East Pittsburgh, Pa.; T. G. LeClair, Chicago, Ill.; Fred R. Maxwell, Jr., Pensacola, Fla.; F. J. Meyer, Oklahoma City, Okla.; W. B. Morton, Glenside, Pa.; W. R. Smith, Newark, N. J.; R. G. Warner, New Haven, Conn.

National Treasurer—W. I. Slichter, Schenectady, N. Y.

National Secretary—H. H. Henline, New York, N. Y.

AIEE Participates in Selecting Signal Corps Library

The AIEE committee on co-operation with war agencies has organized a subcommittee to assist the Signal Corps in selecting the nucleus of scientific and technical material for the recently established Signal Corps Reference Library in Washington, D. C. Nationally known engineering societies have pledged their co-operation in making available for this project books and periodicals that would be difficult to obtain through commercial outlets. The field of interest covers electronics, radio, telephone, telegraph, engineering,

electricity, meteorology, physics, chemistry, electron microphotography, photography (still and motion), cryptology, signal communication, pidgeon breeding and training, direction-finding equipment, and many other technical subjects. Technical books and pamphlets on these subjects will be welcomed and may be shipped directly to the Signal Corps Reference Library, Office of the Chief Signal Officer, War Department, Washington, D. C. Contributors should make use of the special bookmailing rate of 1½ cents per pound, not to exceed 70 pounds in any one package.

Bibliography Published on Electrical Safety

The third bibliography of technical literature entitled "Bibliography on Electrical Safety, 1930–1941" has just been published by the Institute. This publication, sponsored by the AIEE committee on safety, is designed to make available a fund of information on electrical safety which should be of special interest at a time when accident prevention is of national importance. A list of applicable standards, specifications, and safety codes is also included. Information on safety published before 1930 may be located through bibliographies accompanying articles listed.

The items in this bibliography are divided into sections according to subject matter as follows:

A. Electrical Accidents and Their Causes
B. Accident Prevention Methods
C. Safety Codes and Standards
D. Effects of Electric Shock
E. Resuscitation

The "Bibliography on Electrical Safety, 1930–1941" is a 16-page pamphlet, 8½ by 11 inches. It may be obtained from AIEE headquarters, 33 West 39th Street, New York, N. Y., at 25 cents per copy to Institute members (50 cents to nonmembers) with a discount of 20 per cent for quantities of 10 or more mailed at one time to one address. Remittances, payable in New York exchange, should accompany orders.

Additional 1941 District Prizes

The 1941 AIEE North West District prize for initial paper was awarded to Waldo E. Enns (A'37) for his paper entitled "Methods and Apparatus for A-C Network Analysis Using Resistance Networks," which was presented at a meeting of the Portland Section held on April 16, 1941. (See page 479 of this issue for biographical sketch.)

The AIEE 1941 Southern District (4) prize for Branch paper was awarded to Joe E. Woodward (A'42) for his paper entitled "The Vectorscope," which was presented at the annual Southern District convention of Student Branches, held at the University of Alabama, April 3–5, 1941. (See page 480 of this issue for biographical sketch.)

AIEE Wartime Policies Defined

Institute policies and activities under war conditions as formulated by the AIEE committee on planning and co-ordination and adopted by the board of directors on August 7, 1942:

National Conventions and District Meetings: The Institute should continue holding National conventions and District meetings, but all programmed social activities should be omitted, including dinner dances, the ladies' program, and those trips which do not form a part of the technical program. National conventions should be called National technical meetings and District meetings should be called District technical meetings.

Section Meetings: Section meetings should be continued, particularly since they require little, if any traveling and involve no publication. Sections are requested to devote their meetings to war activities to the extent that this would be helpful to the war effort but there is no objection to their also holding meetings which do not meet this criterion.

Technical Papers: All solicited technical programs and papers should be closely related to the war effort. A limited number of unsolicited papers which meet other Institute requirements may be accepted for presentation. However, in accepting such papers, preference will be given to those aiding the war effort, and those not meeting this requirement should constitute a minor part of the total program. In submitting papers to the technical program committee for approval, the technical committee sponsoring the paper shall include in the submittal a statement of the relation of the paper to the war effort and of the reasons for recommending its presentation.

Publications: Publications should follow the same policy as technical papers. The publication committee should take the responsibility for insuring that all publications meet the censorship requirements.

Standards Committee: The standards committee is requested to review carefully the possibility of war emergency standards and devote its attention particularly to stimulating the authorization and production of such standards. It would be desirable for the standards committee to review the situation with War Production Board representatives.

Defense Committee: The defense committee is requested to make a constructive review of the relation of the Institute to war activities and suggest additional activities which the Institute could advantageously undertake in aid of the war effort. (The board of directors, on August 7, changed the name of this committee to committee on co-operation with war agencies.)

Committee on Planning and Co-ordination: It is suggested that the committee on planning and co-ordination continuously examine these and other Institute matters to insure that prompt changes are made, if necessary.

Other Committees: Those committees not specifically mentioned should review their plans and formulate programs of committee work in the spirit of the policies outlined above.

Future AIEE Meetings

Pacific Coast Convention
Vancouver, B. C., September 9–11, 1942

Winter Convention
New York, N. Y., January 25–29, 1943

North Eastern District Meeting
Providence, R. I., April 7–9, 1943

South West District Meeting
Kansas City, Mo., April 28–30, 1943

Lamme Medal Nominations

Attention is called again to the opportunity open to any Institute member to submit nominations for the 1942 AIEE Lamme Medal. All nominations must be received not later than December 1. For further particulars see *Electrical Engineering*, June 1942, page 321.

The 1941 medal was awarded to Forrest E. Ricketts, vice-president, Consolidated Gas Electric Light and Power Company, Baltimore, Md. Addresses delivered at the presentation ceremonies were published in *Electrical Engineering*, August 1942, page 396.

STANDARDS . . .

Standards for Switchgear Apparatus

The general adoption of standard basic impulse insulation levels (Table I) has made practicable the analysis of insulation levels of various types of apparatus and the allocation of proper low-frequency and impulse tests for all voltage classes. Such a study of switchgear equipment has been undertaken by the AIEE protective devices committee.

A brief statement covering preliminary work on outdoor circuit breakers appeared in the September 1941 issue of *Electrical Engineering*, page 448. Further work has resulted in agreement by the AIEE protective devices committee and others on the standard test voltages as given herein for indoor and outdoor circuit breakers, disconnecting switches and bus-bar supports, and assembled switchgear. Switchgear apparatus should be capable of withstanding these test voltages without flashover when tested in accordance with the conditions specified in the individual standards for particular types of apparatus.

These test voltages are presented in order to make the information generally available to the industry as quickly as possible. The same data will be included in the corresponding revised AIEE and American Standards as soon as they are published.

The test voltages for indoor and outdoor power circuit breakers (which will be published as part of American Standards C37.4) are given in Table II with explanatory notes. Bushings used with circuit breakers should conform with the requirements of the Standard for Apparatus Bushings (AIEE Standard 21). Wet tests are not required on completed outdoor circuit breakers as the wet tests which are required on bushings as design tests serve the purpose adequately.

The values for air switches and bus supports will be published in AIEE Standard 22. Those for outdoor devices are shown with explanatory notes in Table III. For indoor air switches and bus supports it has been agreed to accept for the present the values afforded by standard commercial equipment as shown in Table IV.

The work on insulation levels for fuses

Table I. Basic Impulse Insulation Levels

Reference Class (Kv)	Basic Impulse Level (Kv)
1.2	30
2.5	45
5.0	60
8.7	75
	95
15	110
23	150
34.5	200
46	250
69	350
92	450
115	550
138	650
161	750
196	900
230	1,050
287	1,300
345	1,550

Table II. Standard Insulation Test Voltages. Power Circuit Breakers

Insulation Class	Range of Interrupting Rating	Standard Insulation Tests—Withstand Voltage—Kv: Indoor Breakers[a,b] Low Frequency One Minute (Dry)	Indoor Breakers[a,b] Impulse 1.5x40-μsec Full Wave (Pos. or Neg.)	Outdoor Breakers Low Frequency One Minute (Dry)	Outdoor Breakers Impulse 1.5x40-μsec Full Wave (Pos. or Neg.)
2.5	25,000 to 50,000 kva	15	45 ... 30[c]	15	45
	Above 50,000 kva	19	60 ... 45[c]	19	60
5.0	25,000 kva and above	19	60 ... 45[c]	19	60
7.5	25,000 to 150,000 kva	26	75 ... 60[c]	26	75
	Above 150,000 kva	36	95 ... 75[c]	36	95
15	Air and oil 25,000 to 250,000 kva, also, oil 500,000 kva with 3 phases in one tank, and to comparable air breakers above 250,000 to 500,000 kva	36	95 ... 75[c]	50	110
15	Oil breaker rated 500,000 kva and above with each phase in one tank and to comparable air breakers 500,000 kva and above	50	110[d] ... 95[c]	50	110
23	All interrupting ratings	60	150[d]	60	150
34.5	All interrupting ratings	80	200[d]	80	200
46	All interrupting ratings			105	250
69	All interrupting ratings			160	350
92	All interrupting ratings			210	450
115	All interrupting ratings			260	550
138	All interrupting ratings			310	650
161	All interrupting ratings			365	750
196	All interrupting ratings			425	900
230	All interrupting ratings			485	1,050
287.5	All interrupting ratings			590	1,300
345	All interrupting ratings			690	1,550

a. When the dielectric strength of a circuit breaker is dependent upon taping of the leads, or the use of special insulation, such taping or special insulation may be used when the factory test is made.

b. For indoor breakers these impulse test values become effective July 1, 1943.

c. Applied to tests across open contacts of magnetic-type air breakers only. These values are below the basic insulation levels, but they represent present-day design practice. It is the intention that these values are to be increased where possible.

d. Where indoor breakers rated at 15, 23, and 34.5 kv are used at lower voltages, or applied on grounded neutral systems where adequate surge or overvoltage protection is provided, the impulse tests may be specified as 95, 110, and 150 kv, respectively. Such applications should be given special consideration.

Table III. Standard Insulation Test Voltages. Outdoor Air Switches and Bus Supports

Insulation Class	Standard Insulation Tests—Withstand Voltage—Kv: Low Frequency One Minute (Dry)	Impulse 1.5x40-μsec Full Wave (Pos. or Neg.)
7.5	36	95
15	50	110
23	60	150*
34.5	80	200*
46	105	250*
69	160	350
92	210	450**
115	260	550
138	310	650**
161	365	750
196	425	900
230	485	1050
287	590	1300
345	690	1550

* For certain apparatus including air switches and bus insulators, the impulse levels indicated shall become effective on July 1, 1943; in the interim, and for existing designs of this equipment, values of 145, 190, and 240 kv will be recognized as exceptions for these three classes respectively.

** There is no standard switch and bus insulator available for this impulse level. When required, use the next higher level.

Air switches in the full open position shall be capable of withstanding between live parts voltage tests of 10% in excess of the maximum voltage test which they shall withstand to ground.

Table IV. Indoor Air Switches and Bus Supports

Insulation Class*	Standard Insulation Tests—Withstand Voltage—Kv: Low Frequency One Minute (Dry)	Impulse 1.5x40-μsec Full Wave (Pos. and Neg.)
2.5/5	19	45
5/7.5	26	60
7.5/15	36	95
15/23	60	110
23/34.5	80	150

* The first figure (left hand) in Insulation Class applies to devices for fully insulated systems. The second figure (right hand) may apply to devices for grounded neutral systems where adequate surge voltage protection is provided, or to systems not exposed to lightning.

These values are below the basic insulation levels, but they represent present day design practice.

000 volts and above (AIEE report on a proposed Standard) is still in process. However, for outdoor fuses rated 23 kv and above the approved test voltages are the same as given in Table II for outdoor breakers of the same voltage class, with the provision that the 23-, 34.5-, and 46-kv air switches would not have to meet the new impulse test values until July 1, 1943. Complete outdoor fuses rated 23 kv and above should also withstand a 10-second wet test of twice rated voltage plus 1,000 volts.

Due to complexity of switchgear assemblies covered by AIEE Standard 27, it has been impractical to agree on impulse tests for such complete equipment. However, the low-frequency tests given in Table V appear in the AIEE revised Standard 27.

Table V. Standard Insulation Test Voltages

Switchgear Assemblies Rated 2,500 V and Above

When high potential d-c tests are made, the d-c values shall not exceed 1.4 times the corresponding 60 cycle rms test voltage value. Potential transformers having inherently lower insulation strength should be disconnected for these tests

Insulation Class Kv	Switchgear Assemblies With Power Circuit Breakers Having the Following Range of Interrupting Ratings	Standard Insulation Tests 60 Cycle—Kv
2.5	25,000 to 50,000 kva	15
	Above 50,000 kva	19
5.0	25,000 kva and above	19
7.5	25,000 to 150,000 kva	26
	Above 150,000 kva	36
15	Air and oil 25,000 to 250,000 kva, also, oil 500,000 kva with 3 phases in one tank, and to comparable air breakers above 250,000 to 500,000 kva	36
15	Oil with each phase in one tank and to comparable air breakers 500,000 kva and above	50
23	All interrupting ratings	60
34.5	All interrupting ratings	80

Note: Supplementary wet test on entrance bushings for switchgear assemblies for outdoor use: As a supplementary test, entrance bushings on switchgear assemblies for outdoor use should be capable of withstanding for ten seconds a dielectric wet test as a design test only at twice rated voltage plus 1,000 volts. This assumes a precipitation of two-tenths inch (5.08 mm) per minute at an angle of 45 degrees from the perpendicular with water having a resistivity of 6,000–8,000 ohms per inch cube (51,200–20,300 ohms per centimeter cube).

Standard dielectric tests as of the date of issuance of this standard are low frequency only. Impulse voltage tests will be added when agreement is reached concerning the values to be used for switchgear assemblies.

Canadian Sales of "Definitions of Electrical Terms"

Copies of the American and Canadian Standard, C42, "Definitions of Electrical Terms" may be obtained by residents of Canada directly from The Canadian Engineering Standards Association, National Research Building, Ottawa, Ont., at $1.15 per copy, a cost lower than it is possible for them to obtain copies directly from AIEE headquarters in New York, N. Y. This is because quantity purchase by the CESA permits some reduction on the usual custom charges on single copies mailed to Canada from the United States. Over 9,000 copies of C42 have already been placed in the hands of engineers, scientists, and many other interested individuals throughout the United States and Canada.

PERSONAL ••••

S. H. Mortensen (A'09, F'20) engineer in charge of a-c design, Allis-Chalmers Manufacturing Company, Milwaukee, Wis., has been appointed chief electrical engineer of that company's plants at West Allis, Wis., Cincinnati, Ohio, Boston, Mass., and Pittsburgh, Pa. He was born at Eskelund, Denmark, on November 4, 1878, and graduated from the Polytechnicum of Mittweida with the degrees of mechanical and electrical engineer in 1902. He joined the mechanical engineering department of the Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa., in 1902. In 1905 he was employed by the Bullock Electric Manufacturing Company, Cincinnati, Ohio. He joined the Allis-Chalmers company in 1908 and was made designing electrical engineer for d-c motors and generators in that year. In 1909 he became designing electrical engineer for a-c turbogenerators. He was placed in charge of the design of synchronous motors and generators in 1911. In 1932 he was made engineer in charge of a-c design. He has been active in the development of self-starting synchronous motors, synchronous condensers, and turbogenerators. He is the author of a textbook on the design of motors and generators.

N. B. Higgins (A'19, M'27) chief engineer, Safe Harbor Water Power Corporation and Pennsylvania Water and Power Company, both of Baltimore, Md., has been elected president of the Safe Harbor company. He has resigned his position with the Pennsylvania company. Born on February 15, 1885, at Morris Run, Pa., he received the degree of bachelor of science in civil engineering in 1909 from Pennsylvania State College. He was engaged in civil engineering work from 1910 to 1913, when he became chief draftsman, Pennsylvania Water and Power Company. In 1918 he was made engineer of design and maintenance, and in 1919, assistant chief engineer. In 1929 he became assistant chief engineer with the Safe Harbor Water company also. Since 1933 he had been chief engineer of both the Pennsylvania and Safe Harbor companies. He played a large part in the design and construction of the Holtwood hydroelectric development of the Pennsylvania Water and Power Company and the Safe Harbor hydroelectric project. He is also a member of The American Society of Mechanical Engineers, the American Society for Testing Materials, and the American Welding Society.

C. A. Molsberry (A'29) engineer, United Illuminating Company, New Haven, Conn., has been appointed general superintendent of production. He received the degree of bachelor of science in electrical engineering from Iowa State College. In 1922 he was employed by the General Electric Company in the testing department. In 1923 he entered the switchgear department, in 1924 the central-station department, and in 1928 he was appointed engineer at the New Haven office. He joined the United company in 1935 as district engineer at New Haven. He was general engineer for the company from 1936 to 1939, when be became assistant manager of engineering. **P. V. Plummer** (A'33) engineering department, has been appointed assistant to Mr. Molsberry in charge of design and construction. He joined the company in 1928 and in 1930 became assistant to the chief operator in charge of construction and maintenance. In 1940 he was appointed design and construction engineer for the generating department.

W. E. Enns (A'37) electrical engineer, Portland (Oreg.) General Electric Company, has received the 1941 AIEE District 9 prize for initial paper for his paper, "Methods and Apparatus for A-C Network Analysis Using Resistance Networks." He was born on November 8, 1901, Trenton, Mo., and received the degree of bachelor of science in electrical engineering from the University of California. From 1925 to 1929 he was employed as senior electrical designer by the Southern California Edison Company, Los Angeles, Calif., and in 1929 he joined Electrical Research Products, Inc., Los Angeles. He became electrical draftsman in the engineering department of the Bureau of Power and Light, Los Angeles, Calif., in 1935, and in 1936 he joined the Portland (Oreg.) General Electric Company as an assistant electrical engineer. In 1941 he was appointed electrical engineer. He is also a member of Eta Kappa Nu.

C. L. Matthews (A'09, F'27) former vice-president and general manager, W. N. Matthews Corporation, St. Louis, Mo., has been elected president of that company. In 1899 he joined the Packard Electric Company, Warren, Ohio, and the following year he was employed in the drafting department of the Packard Motor Car Company, Warren, Ohio. He joined the firm of W. N. Matthews and Brother, St. Louis, Mo., as junior partner in 1901 and has been with that company or its successors since then. He has been in charge of engineering for the Matthews company since 1901 and in that capacity has worked on the development, design, and produc-

tion of electric devices. In 1908 he began the development of fuse and disconnecting switches. He is the holder of several patents.

H. B. Reynolds (M'41) mechanical engineer, New York City Transit System, has been appointed superintendent of motive power of that company's Interborough Rapid Transit division. He was employed by the Interborough Rapid Transit Company, New York, N. Y. from 1914 to 1917. After working as mechanical assistant to the superintendent of motive power, United Railways and Electric Company, Baltimore, Md., and as fuel engineer with the United States Government, Bureau of Mines, he returned to the Interborough Rapid Transit Company in 1919 as mechanical research engineer. When that company was taken over by the New York City Transit System, he remained as mechanical engineer with the IRT division.

Bern Dibner (A'23, F'42) vice-president and general manager, Burndy Engineering Company, New York, N. Y., has been commissioned as a captain in the United States Air Corps. **Marvin Lee** (A'35, M'41) chief engineer of the Burndy company has been elected acting general manager. He was graduated from Brooklyn Polytechnic Institute in 1922 with the degree of electrical engineer and has been with the Burndy company since 1925.

C. L. Derrick (A'40) engineer, Public Service Electric and Gas Company, Irvington, N. J., has been appointed assistant engineer of the Hartford (Conn.) Electric Light Company. He was graduated from Lehigh University with the degree of electrical engineer in 1923 and in that year joined the Public Service Electric and Gas Company as a cadet engineer. From 1926 to 1936 he was assistant engineer and in 1936 he was made engineer.

J. W. McLaughlin (A'39) former associate engineer, National Power Policy Committee, Washington, D. C., who is now a lieutenant commander in the United States Naval Reserve has been appointed chief of the power and electrical unit and also has been named Navy clearance officer with the power branch of the War Production Board, for the priorities division of the Army and Navy munitions board.

R. E. Greene (A'26) senior engineer, engineering division, Detroit (Mich.) Edison Company, has been appointed construction engineer. In 1919 he was employed in the testing department of the General Electric Company, Schenectady, N. Y., and in 1926 he was transferred to the central-station engineering department. In 1937 he entered the construction bureau of the Detroit Edison Company.

J. R. Murphy (A'20) manager, General Electric Company, Spokane, Wash., has been assigned to represent that company in Washington, D. C. He will be succeeded by **J. F. Gogins** (A'40) salesman, who entered the General Electric Company's test course, Schenectady, N. Y., in 1930. He joined the Spokane office in 1935.

J. E. Woodward (A'42) second lieutenant, United States Army, was awarded the AIEE 1941 Southern District (4) prize for Branch paper for his paper, "The Vectorscope." The award was presented at the annual Southern District convention of Student Branches, held at the University of Alabama, April 3–5, 1941. He was born in Greenville, S. C., on October 14, 1919, and was graduated with the degree of electrical engineering from Clemson College, June 1941. After a short time as student engineer at the Philadelphia, Pa., works of the General Electric Company, he resigned to enter the army. He also is a member of Tau Beta Pi and Phi Kappa Phi.

William H. Harrison (A'20, F'31) on leave as vice-president and chief engineer of the American Telephone and Telegraph Company, New York, N. Y., and recently appointed colonel in the United States Army has become brigadier general in charge of production activities of the Services of Supply. He is a past president (1937–38) and vice-president (1935–37) of the AIEE.

C. O. Bickelhaupt (M'22, F'28) vice-president, American Telephone and Telegraph Company, New York, N. Y., is now a colonel in the United States Army, serving as assistant to the chief signal officer of the Signal Corps, Washington, D. C. (For a complete biographical sketch, see *EE, Feb. '42, p. 94.*)

F. C. Todd (A'27) assistant professor, mineral industries experiment station, Pennsylvania State College, State College, Pa., has received the Charles B. Dudley Medal of the American Society for Testing Materials for the paper, "Studies on Measurement of Water Vapor in Gases," written in collaboration with A. W. Gauger.

Gano Dunn (A'91, F'12) president, J. G. White Engineering Corporation, New York, N. Y., has received an honorary degree of doctor of engineering from Lehigh University. Doctor Dunn is an AIEE past president, and has received the Edison and Hoover Medals, in addition to other honors and honorary degrees.

W. V. Kahler (M'39) chief engineer, Illinois Bell Telephone Company, Chicago, who has been on leave of absence serving as head of the construction branch of the production division of the War Production Board, has been appointed head of a new bureau consolidating WPB construction functions.

G. W. Hart (A'31) sales consultant, Ebasco Services, Inc., New York, N. Y., has joined the Government contract service staff of the radio division of the Western Electric Company, New York, N. Y. He had been with Ebasco Services Inc., since 1936.

J. A. Morris (A'31) meter engineer, Sao Paulo (Brazil) Tramway, Light, and Power Company, Ltd., is now associated with the American Gas and Electric Service Corporation, New York, N. Y. He had been employed by the Sao Paulo Tramway, Light, and Power Company since 1928.

E. W. Kimbark (A'27, M'35) associate professor and acting chairman of the electrical engineering department, Northwestern University, Evanston, Ill., is on leave of absence at Massachusetts Institute of Technology, Cambridge, teaching special courses for Army and Navy officers.

L. M. Goldsmith (M'26) chief engineer, engineering and construction department, Atlantic Refining Co., Philadelphia, Pa., received recently an honorary degree of doctor of science from Drexel Institute of Technology.

F. W. Bliss (A'30) New England district manager, sales development department, General Electric Company, Boston, Mass., is serving as co-ordinator for the city of Boston on the Massachusetts Industrial Committee for National Defense.

R. B. Shepard (A'25, F'36) electrical engineer, Underwriters Laboratories, New York, N. Y., has been appointed deputy chief of the simplification branch of the bureau of industrial conservation of the War Production Board, Washington, D. C.

C. C. Hutchins (A'23, M'29) electrical engineer, Elliott Company, Pittsburgh, Pa., has been appointed executive engineer in charge of product engineering at that company's Ridgway works. He has been with the Elliott Company since 1927.

Joseph Clark (A'26, M'35) assistant engineer, electrical engineering department, Consolidated Edison Company of New York (N. Y.), is on leave of absence, now serving with Jackson and Moreland, Boston, Mass.

E. L. Phillips (M'26) chairman of the board, Long Island Lighting Company, New York, N. Y., has been awarded the honorary degree of doctor of laws by Ohio Wesleyan University by Florida Southern College.

J. V. Wall (A'27) electrical engineer, Elwood Ordnance Plant, Sanderson and Porter, consulting engineers, is now associated with Vern E. Alden, consulting engineer, with headquarters at Chicago, Ill.

T. J. Higgins (A'40) assistant professor, department of electrical engineering, Tulane University, New Orleans, La., has been appointed associate professor in the department of electrical engineering, Illinois Institute of Technology, Chicago.

W. J. Ellenberger (A'31, M'38) power engineer, Potomac Electric Power Company, Washington, D. C., is now a first lieutenant in the Signal Corps of the United States Army.

F. H. McIntosh (M'37) technical director, Fort Industry Company, Toledo, Ohio, has become chief of the radio section of the

communications branch, division of industry operations, War Production Board.

C. F. Kettering (A'04, F'14) vice-president in charge of research, General Motors Corporation, Dayton, Ohio, has been named consultant to the radio and radar branch of the War Production Board.

L. E. Messinger (A'30) president, Canadian Line Materials, Ltd., Toronto, Ont., has been made assistant to the chairman of the War Time Trade and Price Board of Canada.

W. R. Lyon (A'20, M'26) factory representative United States Army Air Corps, with Wright Aeronautical Corporation, Lockland, Ohio, is now stationed at South Bend, Ind., as resident representative.

C. S. Redding (A'12, M'41) president, Leeds and Northrup Company, Philadelphia, Pa., has been elected president of the Franklin Institute. He was formerly a manager of that organization.

F. A. Hansen (M'31) managing director, The Western Institute of Light and Vision, Los Angeles, Calif., recently received the honorary degree of master of science from the University of Southern California.

Vannevar Bush (A'15, F'24) president, Carnegie Institute of Washington (D. C.) has been awarded the honorary degree of doctor of laws by Yale University.

S. E. Gates (A'36) manager, Los Angeles (Calif.) office, General Electric Company, has been elected president of the Pacific Coast Electrical Association.

C. C. Sowards (A'40) sales engineer, Copperweld Steel Company, New York, N. Y., is now in the United States Army stationed at a Midwest ordnance plant.

OBITUARY

William Herrman Brenner (A'93, M'94) retired engineer, Atlanta, Ga., died on June 20, 1942. He was born at Augusta, Ga., on December 20, 1860. From 1883 to 1886 he was employed in the engineering department of the New York (N. Y.) Edison Company, and from 1886 to 1887 he was superintendent and electrician with the Edison Electric Illuminating Company, Cincinnati, Ohio. He was engaged in electric-light and railway construction in Tokyo, Japan, from 1887 to 1891, when he became district engineer for the Edison General Electric Company, Toronto, Ontario. From 1892 to 1894 he was an electrical engineer with the Montreal (P. Q.) Street Railway. In 1894 he joined the Electrical and Mechanical Engineering Company, New York, N. Y., and the following year he joined the Electric Storage Battery Company, Philadelphia, Pa., with headquarters in New York. In 1896 he became construction engineer for the New York and Staten Island Electrical Company, Livingston, N. Y. From 1897 to 1900 he was engineering manager for Frazer and Company, Yokohama, Japan, and from 1900 to 1909 he was managing director and chief engineer at the Zemma Works, Yokohama, Japan. In 1909 he became manager of the British Columbia Manufacturing Company, New Westminster, and in 1911 he joined the Electromotor Equipment Company, London, England, as managing director. He served as director, Gerente de la Fabrica Cia, Anglo-Espanola de Cemento Portland, Matillas, Spain, from 1913 to 1929 when he retired. He was also a member of The American Society of Mechanical Engineers.

Frederick A. Allner (A'12, M'14) president, Safe Harbor Water Power Corporation, Baltimore, Md., died on July 18, 1942. He was born at Skytal, Austria, on July 19, 1882, and was graduated from the Technical College of Prague with the degree of mechanical engineer in 1904. From 1905 to 1907 he was employed as designing engineer for a-c generators, motors, and transformers with the Elektrizitaets Aktein Gesellschaft vormals Kolben and Company, Prague, and in 1907 he joined the Gesellschaft fuer Elektrische Industrie, Karlsruhe, Germany, as a designing and testing engineer for turbogenerators. He was employed as an engineer in the standard practice and shop management department, American Locomotive Company, Montreal (P. Q.) Locomotive Works in 1908 and the following year he became electrical and mechanical engineer for the Shawinigan Water and Power Company, Montreal, P. Q. In 1909 he joined the McCall Ferry Power Company, Holtwood, Pa. (later the Pennsylvania Water and Power Company) as assistant chief engineer, in 1911 became general superintendent, and later vice-president. He became general superintendent of the Safe Harbor Water Power Corporation in 1929 and was elected president in 1940. He was also a member of The American Society of Mechanical Engineers and the American Society of Civil Engineers.

John Coffee Hays (A'04, M'13) executive vice-president, Stone and Webster Engineering Corporation, New York, N. Y., died on July 21, 1942. He was born on January 5, 1883, in Tulane County, Calif. From 1899 to 1903 he was employed by the Mount Whitney Power Company, Visalia, Calif., except for a brief period with Henshaw Bulkly and Company, San Francisco, Calif. During 1903–04 he was employed by the Stanley Electric Manufacturing Company, Pittsfield, Mass. In 1904 he joined L. B. Stillwell, consulting engineer, New York, N. Y. In 1907 he became president, general manager, and consulting engineer of a group of utilities and hydroelectric projects in California, including the Mount Whitney Power Company, Yosemite Power Company, Tuolumino Power and Light Company, La Grange Water and Power Company, and Mount Shasta Power Company. In 1915 he went to San Francisco, Calif. as a consulting engineer and in 1919 he joined the Stone and Webster Engineering Corporation as a hydraulic engineer. He became vice-president of that company in 1929 and executive vice-president in 1938. He was also a member of the American Society of Civil Engineers and The American Society of Mechanical Engineers.

Henry Gerber Reist (A'90, M'94, F'13) retired head of the motor and generating engineering department, General Electric Company, Schenectady, N. Y., died July 5, 1942. He was born at Mount Joy, Pa., on May 27, 1862, and was graduated from Lehigh University with the degree of mechanical engineer in 1886. After working in the testing and drafting departments of the Foundry and Machine Company, Harrisburg, Pa., he joined the Thomson-Houston Electric Company, Lynn, Mass. (later a part of the General Electric Company), in 1889. In 1894 he took charge of the design and construction of alternating current machinery and in 1931 he retired. He held a number of patents for inventions, among which was a fabricated structure to replace castings in electric apparatus. He was a member and past vice-president of The American Society of Mechanical Engineers, and a member of the American Association for the Advancement of Science. He was also a member of Tau Beta Pi and Sigma Xi.

Hewlitt Scudder (A'99) retired assistant patent attorney, General Electric Company, Schenectady, N. Y., died July 31, 1942. He was born in New York, N. Y., on August 9, 1875 and received the degrees of bachelor of arts from Yale University in 1896 and master of arts and electrical engineer from Columbia University in 1899. He joined the General Electric Company at Schenectady, N. Y., in 1902 as a test engineer. In 1905 he was transferred to the railway engineering department and in 1907 he joined the patent department. In 1911 he was placed in charge of foreign patents and when the International General Electric Company was formed, he was placed in charge of its foreign work. He was also a member of The American Society of Mechanical Engineers.

Charles L. Cornell (A'90, M'95) retired electrical engineer and former executive vice-president of the Niles-Bement-Pond Company, New York, N. Y., and its subsidiary, the Pratt and Whitney Machine Tool Company, died July 18, 1942. He was born at Hamilton, Ohio, on September 7, 1861, and was graduated from Cornell University in 1889. From 1889 to 1890 he was construction engineer at Kearney, Nebr. He was employed by the Omaha (Nebr.) Street Railway during 1890, and later he was engaged in business as a construction engineer and contractor in the Middle West. In 1899 he had a part in organizing the Niles-Bement-Pond Company and was its treasurer until 1907,

when he was made executive vice-president. He retired in 1925.

Dick Pyper (A'29) foreman, hydroelectric power station, Compania Minera Choco Pacifico, Andagoya, Colombia, South America, died on March 6, 1942. He was born on April 11, 1900, at Oostwoud, Holland. In 1920 he was employed by the Toronto Power Company, Niagara Falls, Ontario and in 1926 he went to Chile to serve as switchboard operator with the Braden Copper Company. In 1927 he became chief operator and load dispatcher and the following year he became also relief generating-station foreman. In 1930 he was employed by the Southern California Edison Company, Big Creek, Calif., and from 1934 to 1938 he was an operator at the hydroelectric powerhouse, Turlock Irrigation District, La Grange, Calif.

Richard Thomas Durran (A'05) electrical engineer, London, England, died on June 5, 1942. Born at London on April 16, 1876, he was a graduate of Finsbury Technical College. After being employed by J. G. Statter and Company for a year, he was assistant to the editor of a publication entitled, "Electrician." Later he was employed by W. H. Allen Son and Company, Ltd., Bedford, England, as general mechanical and electrical engineer. He joined the Allgemeine Elektricitats Gesellschaft, Berlin, Germany, as an engineer in the foreign department and later was appointed manager.

MEMBERSHIP

Applications for Election

Applications have been received at headquarters from the following candidates for election to membership in the Institute. Names of applicants in the United States and Canada are arranged by geographical District. If the applicant has applied for direct admission to a grade higher than Associate, the grade follows immediately after the name. Any member objecting to the election of any of these candidates should so inform the national secretary before September 30, 1942, or November 30, 1942, if the applicant resides outside of the United States or Canada.

United States and Canada

1. North Eastern

Allain, A. R., Jr., Vulcan Electric Corporation, Danvers, Mass.
Fagen, M. D. (Member), Massachusetts Institute of Technology, Cambridge, Mass.
Goodwin, F. R., Narragansett Electric Company, Providence, R. I.
Guillemette, J. D. (Member), Jenks and Ballou, Providence, R. I.
Jerneckis, A. P., General Electric Company, Schenectady, N. Y.
Klauber, P. M., General Electric Company, Schenectady, N. Y.
Nelson, E. J., Rochester Gas and Electric Corporation, Rochester, N. Y.
Reinhardt, H. (Member), Hygrade Sylvania Corporation, Danvers, Mass.
Sills, R. H., Eastman Kodak Company, Rochester, N. Y.
Wight, J. C., General Electric Company, Bridgeport, Conn.

2. Middle Eastern

Anderson, R. P. (Member), Cutler Hammer, Inc., Cleveland, Ohio.
Byers, G. M., Navy Department, Philadelphia, Pa.
Daugherty, W. E., Bethlehem Steel Company, Baltimore, Md.
Foss, F. A. (Member), United States Corps of Engineers, Lockbourne Army Airbase, Ohio.
Frye, H. B., United States Engineer Office, Wright Field, Dayton, Ohio.
Grant, R. M., Allis-Chalmers Manufacturing Company, Pittsburgh, Pa.
Gregory, C. A., Jr., Washington and Jefferson College, Washington, Pa.
Gross, G. C. (Member), Federal Communications Commission, Washington, D. C.
Lewis, J. H., Philadelphia Electric Company, Philadelphia, Pa.
Lynch, N. C., Wm. E. Kingswell, Inc., Washington, D. C.
Newton, G. C., Jr., York Safe and Lock Company, York, Pa.
Potter, E. G., The Lima Armature Works, Lima, Ohio.
Saunders, C. C. (Member), E. I. Du Pont de Nemours, Wilmington, Del.
Strickler, W. A., Jr., The North Electric Manufacturing Company, Galion, Ohio.

3. New York City

Armstrong, W. P., George S. Armstrong and Company, Inc., New York, N. Y.
Grossfeld, C. (Member), Bronx Vocational High School, Bronx, N. Y.
Key, E. G., United States Army, Signal Corps, Fort Monmouth, N. J.
Kohl, H. S., Nichols Engineering and Research Corporation, New York, N. Y.
Lange, W. F., Gibbs and Cox, Inc., New York, N. Y.
Miner, R. Y. (Associate re-election), Arma Corporation, Brooklyn, N. Y.
Stobbe, J. A., 63 Wall Street, New York, N. Y.
Straube, W. T. (Member), 653—53d Street, Brooklyn, N. Y.
Valesio, M. J. (Associate re-election), Office of the Borough President of Manhattan, New York, N. Y.
Witkus, V. W., Western Electric Company, Kearny, N. J.

4. Southern

Bason, G. F. (Associate re-election), Durham, N. C.
Brumleve, C. C., Thermex Division–Girdler Corporation, Louisville, Ky.
Fortney, J. G., Reynolds Alloys Company, Lister, Ala.
Goldan, A. S. (Associate re-election), Pan American Airways, Miami, Fla.
King, H. W. (Member), Sangamo Electric Company, Louisville, Ky.
Lamb, R. V., 207 N. Martin Street, Elizabeth City, N. C.
Parker, G. R., Electric Power Board, Chattanooga, Tenn.
Parker, R. M. (Member), United States Engineer Office, Fort Custis, Va.
Rackle, E. E., Waterman Steamship Corporation, Mobile, Ala.
Webb, H. E., Jr., United States Army Air Forces, Tuskegee Army Flying School, Tuskegee, Ala.

5. Great Lakes

Amos, L., Delco Remy, Anderson, Ind.
Barnes, E. W., Sargent and Lundy, Chicago, Ill.
Borland, C. A., Western Electric Company, Inc., Chicago, Ill.
Buchanan, G. E. (Associate re-election), Delta-Star Electric Company, Chicago, Ill.
Deppe, R. M. (Member), Commonwealth Edison Company, Chicago, Ill.
Gwyn, C. B., Jr. (Member), Fansteel Metallurgical Corporation, North Chicago, Ill.
Kirwen, M. S. (Associate re-election), The Commonwealth and Southern Corporation, Jackson, Mich.
Kroomian, C. W., General Electric Company, Fort Wayne, Ind.
Reynolds, F. B. (Member), Graybar Electric Company, Madison, Wis.
Sinish, R. D., General Electric Company, Fort Wayne, Ind.
Smith, R. E., Wincharger Corporation, Sioux City, Iowa.
Smith, W. H., Jr., Tri-State College, Angola, Ind.
Swinney, J. W., Delco Remy Division of General Motors, Anderson, Ind.
Watson, R. W., Westinghouse Electric and Manufacturing Company, Chicago, Ill.
Wirt, J. R., Delco Remy Division, General Motors Corporation, Anderson, Ind.

6. North Central

Stark, R. L., United States Bureau of Reclamation, Kremmling, Colo.
World, R. W., Bureau of Reclamation, Denver, Colo.

7. South West

Bodin, J. A., Schlumberger Well Surveying Corporation, Houston, Tex.
Brown, H. H., St. Louis Ordnance Plant, St. Louis, Mo.
Eisler, H. C., Kansas Electric Power Company, Emporia, Kans.
Gould, H. M. (Member re-election), Smith, Hinchman, and Grylls, Inc., Lake City, Mo.
Kersh, R. S., Westinghouse Electric and Manufacturing Company, Houston, Tex.
Moore, J. H., Rural Electrification Administration, St. Louis, Mo.

8. Pacific

Boyd, W. E., Pacific Electric Motor Company, Oakland, Calif.
Caswell, R. A. (Member), United States Army Signal Corps, Fort Mason, San Francisco, Calif.
Dahlstrum, A., Vultee Aircraft, Inc., Vultee Field, Calif.
Goodner, F. S., Mare Island, Calif.
L'Hommedieu, W. R., Westinghouse Electric and Manufacturing Company, Los Angeles, Calif.
Marrs, T., Bureau of Reclamation, Yuma, Ariz.
Moler, M. A., United States Maritime Commission, Oakland, Calif.
Peterson, N. J., General Electric Company, San Francisco, Calif.
Woodard, M. L., Maywood Limited, San Francisco, Calif.

9. North West

James, S. D., Lyle, Wash.
Lean, B. W., City Light Department, Cheney, Wash.

10. Canada

Alexander, F., Burrard Dry Dock Company, Ltd., North Vancouver, B. C.
Donald, H. G., Lloyd's Register of Shipping, Vancouver, B. C.

Total, United States and Canada, 80

Elsewhere

Amster, M. N., The Panama Canal, Diablo Heights, Canal Zone.
Boyce, H. (Member), Royal Navy, Cape Town, South Africa.
Colon, J. (Member), Hidroelectrica del Estado, Quetzaltenango, Guatemala, Central America.
Cox, H. (Member), Derbyshire and Nottinghamshire Electric Power Company, Derbyshire, England.
Davis, P., P.W.D. Electricity Branch, Lyallpur Division, Punjab, India.
Gonzalez, E. (Member), Bolivian Power Company Ltd., Oruro, Bolivia, S. A.
Harskin, M., British Power Transformer Company, Ltd., Enfield, Middlesex, England.
Jenkins, D. F. L. W., Messrs. Johnson and Phillips Ltd., London, S.E. 7, England.
Jennings, F. M. (Member), United States Corps of Engineers, Ancon, Canal Zone.
Khan, M. A. (Member), Manavadar, Kathiawar, India.
Satyanarayana, A. V., Indian Army Ordnance Corps, Base Post Depot, Karachi, Jebbulpure, India.

Total, elsewhere, 11

Addresses Wanted

A list of members whose mail has been returned by the postal authorities is given below, with the addresses as they now appear on the Institute record. Any member knowing of corrections to these addresses will kindly communicate them at once to the office of the secretary at 33 West 39th St., New York, N. Y.

Abell, Elwyn D., 1168 Glenwood Blvd., Schenectady, N. Y.
Allen, Richard L., 2922—18th St., N. W., Washington, D. C.
Bean, William S., Jr., 1108 Baker Ave., Schenectady, N. Y.
Christiansen, August Glenn, 532—72nd St., Brooklyn, N. Y.
Coryell, Walter R., Central Y.M.C.A., 9th and La Salle Sts., Minneapolis, Minn.
Day, William M., 2821 St. Paul St., Baltimore, Md.
Degentesh, H. E., 310 Riverside Drive, New York, N. Y.
Eager, George S., Jr., 19 Wabeno St., Boston, Mass.
Eddie, W., Jr., 1725 Pierrie Ave., Windsor, Ont., Can.
Evans, T. C., Jr., 160—16th Ave., N. W., Washington, D. C.
Greenlees, Charles R., Jr., 1903 Kalorama Road, Washington, D. C.
Hafely, Charles Harold, 715 W. Maumee, Angola, Ind.
Hilt, William Myron, 30 W. Chicago Ave., Chicago, Ill.
Innis, Harry H., 5325 Forbes St., Pittsburgh, Pa.
Johnson, Joseph E., 1631 S. 49th Court, Cicero, Ill.
Kettering, Clifford C., 403 Westminster, Los Angeles, Calif.
Klein, William, 219 Echo Place, New York, N. Y.
Levy, Harold C., 1523 Stone, Great Bend, Kans.
McConnell, Malcolm E., 5424—5th Ave., Pittsburgh, Pa.
Montgomery, W. E., 401 S. Electric, Alhambra, Calif.
Moore, W. H., 600 Braxton Place, Alexandria, Va.
Mouli, W. C., 555 Chamberlain St., Peterboro, Ont., Can.
Osteen, William C., Southern California Edison Co., Ltd., South Pasadena, Calif.
Schrawder, Robert Rat, 606 Pine St., Lancaster, Pa.
Smith, Henry A., 4232 Baring Ave., East Chicago, Ind.
Taylor, Richard V., 1825 G St., N. W. Washington, D. C.
Warriner, Robert R., 4251 W. Irving Park Road, Chicago, Ill.
Wirpio, Carl I., 1000 Central Ave., Louisville, Ky.

28 Addresses Wanted

Officers and Committees for 1942–43

Officers

President

HAROLD S. OSBORNE — New York, N. Y. (*Term expires July 31, 1943*)

Junior Past Presidents

R. W. SORENSEN — Pasadena, Calif. (*Term expires July 31, 1943*)

DAVID C. PRINCE — Schenectady, N. Y. (*Term expires July 31, 1944*)

Vice-Presidents

District		
2	(To be announced)	
4	J. ELMER HOUSLEY	Alcoa, Tenn.
6	ARTHUR L. JONES	Denver, Colo.
8	WALTER C. SMITH	San Francisco, Calif.
10	C. A. PRICE	Hamilton, Ont.
	(*Terms expire July 31, 1943*)	
1	K. B. McEACHRON	Pittsfield, Mass.
3	CHARLES R. JONES	New York, N. Y.
5	A. G. DEWARS	Minneapolis, Minn.
7	E. T. MAHOOD	Kansas City, Mo.
9	E. W. SCHILLING	Bozeman, Mont.
	(*Terms expire July 31, 1944*)	

Directors

MARK ELDREDGE	Washington, D. C.
C. M. LAFFOON	East Pittsburgh, Pa.
F. J. MEYER	Oklahoma City, Okla.
(*Terms expire July 31, 1943*)	
T. F. BARTON	New York, N. Y.
M. S. COOVER	Ames, Iowa
R. G. WARNER	New Haven, Conn.
(*Terms expire July 31, 1944*)	
L. R. GAMBLE	Spokane, Wash.
T. G. LeCLAIR	Chicago, Ill.
FRED R. MAXWELL, JR.	Pensacola, Fla.
(*Terms expire July 31, 1945*)	
K. L. HANSEN	Milwaukee, Wis.
W. B. MORTON	Glenside, Pa.
W. R. SMITH	Newark, N. J.
(*Terms expire July 31, 1946*)	

National Treasurer

W. I. SLICHTER — Schenectady, N. Y. (*Term expires July 31, 1943*)

National Secretary

H. H. HENLINE — New York, N. Y. (*Term expires July 31, 1943*)

Local Honorary Secretaries

AUSTRALIA—V. J. F. Brain, Department of Public Works, Bridge Street, Sydney, N.S.W.

BRAZIL—Richard H. Bowles, Sao Paulo Tramway Light and Power Company, Sao Paulo.

ENGLAND—A. P. M. Fleming, Metropolitan-Vickers Electric Company, Trafford Park, Manchester.

FRANCE—A. S. Garfield, 173 Boulevard Haussmann, Paris, 8E.

INDIA, NORTHERN—V. F. Critchley, 3 Abbot Road, Lahore, Punjab.

INDIA, SOUTHERN—N. N. Iengar, The Tata Power Co. Ltd., Bombay House, Bruce Street, Fort Bombay.

NEW ZEALAND—P. H. Powell, Canterbury College, Christchurch.

SWEDEN—A. F. Enstrom, Ingeniorsvetenskrapsakademien, Stockholm, 5.

TRANSVAAL, SOUTH AFRICA—W. Elsdon-Dew, P. O. Box 4563, Johannesburg.

General Committees

Executive

Harold S. Osborne, *chairman*, 195 Broadway, New York, N. Y.
T. F. Barton — W. I. Slichter
C. R. Jones — R. W. Sorensen
David C. Prince — R. G. Warner

Board of Examiners

A. E. Knowlton, *chairman*, *Electrical World*, 330 W. 42d Street, New York, N. Y.
H. E. Farrer, *secretary*, AIEE, 33 W. 39th Street, New York, N. Y.
P. H. Adams — L. F. Hickernell
M. C. Beebe — Alexander Maxwell
L. W. Chubb — K. B. McEachron
F. E. D'Humy — L. W. W. Morrow
E. D. Doyle — R. C. Roe
J. F. Fairman — H. S. Warren
A. L. Harding — R. J. Wiseman
Sidney Withington

Code of Principles of Professional Conduct

Dugald C. Jackson, *chairman*, 5 Mercer Circle, Cambridge, Mass.
Harry Barker — W. M. Piatt
C. R. Beardsley — Walter C. Smith
D. D. Ewing — G. A. Waters

Constitution and Bylaws

I. Melville Stein, *chairman*, Leeds and Northrup Company, 4901 Stenton Avenue, Philadelphia, Pa.
C. A. Powel, *vice-chairman*, Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa.
Mark Eldredge — W. I. Slichter — R. L. Jones

Edison Medal

Appointed by the president for term of five years

J. W. Barker — N. E. Funk, *chairman* — W. H. Harrison
(*Terms expire July 31, 1943*)
W. B. Kouwenhoven — F. V. Magalhaes — L. W. W. Morrow
(*Terms expire July 31, 1944*)
K. T. Compton — W. D. Coolidge — J. M. Thomson
(*Terms expire July 31, 1945*)
J. T. Barron — R. E. Doherty — J. V. B. Duer
(*Terms expire July 31, 1946*)
F. D. Newbury — David C. Prince — W. E. Wickenden
(*Terms expire July 31, 1947*)

Elected by board of directors from its own membership for term of two years

M. S. Coover — Mark Eldredge — R. W. Sorensen
(*Terms expire July 31, 1943*)
T. F. Barton — T. G. LeClair — K. B. McEachron
(*Terms expire July 31, 1944*)

Ex officio

Harold S. Osborne, president
W. I. Slichter, national treasurer
H. H. Henline, national secretary
(*Terms expire July 31, 1943*)

Finance

T. F. Barton, *chairman*, General Electric Company, 570 Lexington Avenue, New York, N. Y.
C. R. Jones — W. R. Smith

Charles LeGeyt Fortescue Fellowship

C. A. Powel — David C. Prince (*Terms expire July 31, 1943*)
W. F. Davidson — D. F. Miner (*Terms expire July 31, 1944*)
O. E. Buckley, *chairman* — Ernst Weber (*Terms expire July 31, 1945*)

Headquarters

Edward C. M. Stahl, *chairman*, Consolidated Edison Company of New York, Inc., 4 Irving Place, New York, N. Y.
T. F. Barton — H. H. Henline

Lamme Medal

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Nevada, Univ. of, Reno	8	S. G. Palmer
Newark Col. of Engineering, Newark, N. J.	3	F. A. Russell
New Hampshire, Univ. of, Durham	1	W. B. Nulsen
New Mexico State Col., State College	7	M. A. Thomas
New Mexico, Univ. of, Albuquerque	7	H. L. Jones
New York, Col. of the City of, New York	3	Harry Baum
New York Univ., New York	3	P. C. Cromwell
North Carolina State Col., Raleigh	4	L. M. Keever
North Dakota State Col., Fargo	6	H. S. Rush
North Dakota, Univ. of, Grand Forks	6	C. W. Rook
Northeastern Univ., Boston, Mass.	1	R. G. Porter
Northwestern Univ., Evanston, Ill.	5	R. W. Jones
Norwich Univ., Northfield, Vt.	1	D. E. Howes
Notre Dame, Univ. of, Notre Dame, Ind.	5	J. A. Northcott
Ohio Northern Univ., Ada	2	D. S. Pearson
Ohio State Univ., Columbus	2	S. O. Evans
Ohio Univ., Athens	2	W. M. Young
Oklahoma A. & M. College, Stillwater	7	A. Naeter
Oklahoma, Univ. of, Norman	7	C. L. Farrar
Oregon State Col., Corvallis	9	F. O. McMillan
Pennsylvania State Col., State College	2	P. X. Rice
Pennsylvania, Univ. of, Philadelphia	2	S. R. Warren, Jr.
Pittsburgh, Univ. of, Pittsburgh, Pa.	2	R. C. Gorham
Puerto Rico, Univ. of, Mayagues, P. R.	3	G. F. Anton
Pratt Institute, Brooklyn, N. Y.	3	D. H. Wright
Princeton Univ., Princeton, N. J.	2	W. C. Johnson
Purdue Univ., Lafayette, Ind.	5	J. H. Karr
Rensselaer Polytechnic Inst., Troy, N. Y.	1	E. D. Broadwell
Rhode Island State Col., Kingston	1	
Rice Inst., Houston, Tex.	7	C. R. Wischmeyer
Rose Polytechnic Inst., Terre Haute, Ind.	5	C. C. Knipmeyer
Rutgers Univ., New Brunswick, N. J.	3	J. L. Potter
Santa Clara, Univ. of, Santa Clara, Calif.	8	W. J. Warren
South Carolina, Univ. of, Columbia	4	W. M. Bauer
South Dakota State College, Brookings	6	W. H. Gamble
South Dakota State School of Mines, Rapid City	6	E. E. Clark
Southern California, Univ. of, Los Angeles, Calif.	8	J. K. Nunan
Southern Methodist Univ., Dallas, Tex.	7	H. F. Huffman
Stanford Univ., Stanford University, Calif.	8	H. H. Skilling
Stevens Inst. of Technology, Hoboken, N. J.	3	W. L. Sullivan
Swarthmore Col., Swarthmore, Pa.	2	J. D. McCrumm
Syracuse Univ., Syracuse, N. Y.	1	C. W. Henderson
Tennessee, Univ. of, Knoxville	4	W. O. Lefell
Texas A. & M. Col., College Station	7	N. F. Rode
Texas Technological Col., Lubbock	7	C. V. Bullen
Texas, Univ. of, Austin	7	R. A. Galbraith
Tufts College, Tufts College, Mass.	1	A. H. Howell
Tulane Univ., New Orleans, La.	4	
Union Col., Schenectady, N. Y.	1	H. W. Bibber
Utah, Univ. of, Salt Lake City	9	L. Dale Harris
Vermont, Univ. of, Burlington	1	R. O. Buchanan
Villanova Col., Villanova, Pa.	2	H. S. Bueche
Virginia Military Inst., Lexington	4	J. S. Jamison
Virginia Polytechnic Inst., Blacksburg	4	Claudius Lee
Virginia Univ. of, University	4	J. S. Miller
Washington, State College of, Pullman	9	H. F. Lickey
Washington, Univ. of, Seattle	9	R. E. Lindblom
Washington Univ., St. Louis, Mo.	7	D. A. Fischer
West Virginia Univ., Morgantown	2	A. H. Forman
Wisconsin, Univ. of, Madison	5	E. D. Ayres
Worcester Polytechnic Inst., Worcester, Mass.	1	V. Siegfried
Wyoming, Univ. of, Laramie	6	G. H. Sechrist
Yale Univ., New Haven, Conn.	1	A. G. Conrad

Total Branches 124

Local Sections of the Institute

Name	District	When Organized	Membership Aug. 1, 1942	Chairman	Secretary	Secretary's Address
Akron	2	Aug. 12, '20	94	K. F. Sibila	A. G. Seifried	B. F. Goodrich Co., 500 S. Main St., Akron, Ohio
Alabama	4	May 22, '29	44	G. W. McCracken	M. V. Zimmerman	Commonwealth and Southern Corp., Birmingham, Ala.
Arizona	8	Mar. 22, '41	37	G. F. Maughmer	E. A. Gisel	1531 West Encanto Blvd., Phoenix, Ariz.
Boston	1	Feb. 13, '03	516	R. G. Porter	W. I. Middleton	Simplex Wire & Cable Co., Cambridge, Mass.
Central Indiana	5	Jan. 12, '12	133	C. K. Gieringer	J. R. Pies	501 North LaSalle St. Indianapolis, Ind.
Chicago	5	1893	836	J. C. Woods	E. C. Minteer	Minteer & Joeler, 327 So. LaSalle St., Chicago, Ill.
Cincinnati	2	June 30, '20	214	L. J. Dunnewold	F. J. Breen, Jr.	3821 Delmar Ave., Cheviot, Ohio
Cleveland	2	Sept. 27, '07	376	C. A. Harrington	D. Ramadanoff	The National Carbon Co., W. 73rd St. & N.Y.C.R.R., Cleveland, Ohio
Columbus	2	Mar. 17, '22	95	S. A. Martin	S. O. Evans	Ohio State University, Columbus, Ohio
Connecticut	1	Apr. 16, '21	333	A. G. Conrad	C. D. Hewitt	227 Church St., New Haven, Conn.
Denver	6	May 18, '15	180	H. B. Palmer	Hubert Sharp	Mountain States Tel. & Tel. Co., P. O. Box 960, Denver, Colo.
East Tennessee	4	Sept. 2, '36	145	R. A. Hopkins	B. H. McCoin	City of Knoxville Electric Dept., Knoxville, Tenn.
Erie	2	Jan. 11, '18	65	W. I. Linkor	W. D. Bearce	4121 Sassafras St., Erie, Pa.
Florida	4	Jan. 28, '31	111	J. B. Hiers, Jr.	Joseph Weil	University of Florida, Gainesville, Fla.
Fort Wayne	5	Aug. 14, '08	93	S. D. Summers	W. W. Brooks	General Electric Co., Fort Wayne, Ind.
Georgia	4	Jan. 14, '04	119	J. M. Flanigen	Carl Evans	Electrical South, 1020 Grant Bldg., Atlanta, Ga.
Houston	7	Aug. 7, '28	133	P. H. Underwood	S. C. Commander	2615 Fannin St., Houston, Texas
Iowa	5	June 25, '29	84	L. A. Ware	W. B. Boast	Iowa State College, Ames, Iowa
Ithaca	1	Oct. 15, '02	53	H. G. Smith	E. W. Jones	Cornell University, Franklin Hall, Ithaca, N. Y.
Kansas City	7	Apr. 14, '16	137	C. G. Roush	C. M. Lytle	P. O. Box 679, Kansas City, Mo.
Lehigh Valley	2	Apr. 16, '21	188	E. R. Beers	L. Z. Ludorf	Penn. Power and Light Co., 135 N. Washington St., Wilkes-Barre, Pa.
Los Angeles	8	May 19, '08	540	T. M. Blakeslee	P. L. Johnson	Box 5300, Metropolitan Station, Los Angeles, Calif.
Louisville	4	Oct. 15, '26	73	M. M. Hughes	L. G. Weiser	Westinghouse Electric & Mfg. Co., 1618 Heyburn Bldg., Louisville, Ky.
Lynn	1	Aug. 22, '11	186	J. H. Goss	M. S. Wilson	General Electric Co., Factory 2nd L., West Lynn, Mass.
Madison	5	Jan. 8, '09	73	R. R. Knoll	E. J. Van Duesen	2702 Sommers Ave., Madison Wis.
Mansfield	2	Mar. 6, '39	71	H. O. Whiteley	J. M. Robinson	North Electric Mfg. Co., Galion, Ohio
Maryland	2	Dec. 16, '04	322	H. J. Casey	B. Van Ness	1503 Lexington Bldg., Baltimore, Md.
Memphis	4	May 23, '30	56	J. P. Argo	Herman Leightman	Memphis Light, Gas and Water Div., 179 Madison Ave., Memphis, Tenn.
Mexico	3	June 29, '22	53	J. H. Olmedo	G. Robles	La Consolidada, Apartado 81-Bis., Mexico, D.F. Mexico
Michigan	5	Jan. 13, '11	418	M. B. Stout	J. W. Bishop	134 Englewood Ave , Detroit, Mich.
Milwaukee	5	Feb. 11, '10	313	F. W. Bush	T. B. Jochem	Cutler-Hammer, Inc., 315 N. 12th St., Milwaukee, Wis.
Minnesota	5	Apr. 7, '02	98	Wm. Endicott	C. W. Lethert	Northern States Power Co., 15 So. 5th St., Minneapolis, Minn.
Montana	9	June 24, '31	45	D. K. Brake	C. R. Davis	Montana Power Co., Butte, Montana
Muscle Shoals	4	Feb. 18, '38	33	R. C. Fuller	S. J. Wolfenson	T.V.A., Project W3, Wilson Dam, Ala.
Nebraska	6	Jan. 21, '25	59	J. M. Gibb	I. M. Ellestad	Northwestern Bell Telephone Co., Omaha, Nebr.
New Mexico-West Texas	7	Mar. 7, '40	43	F. A. Decker	L. R. Hammond	Phelps Dodge Corp., El Paso, Texas
New Orleans	4	Dec. 8, '33	133	J. V. Hay	F. E. Johnson	317 Baronne St., New Orleans, La.
New York	3	Dec. 10, '19	3,447	C. C. Whipple	M. D. Hooven	Public Service Electric & Gas Co., 80 Park Pl., Newark, N. J.
Niagara Frontier	1	Feb. 10, '25	198	J. F. Oehler	E. R. Paige	Buffalo Niagara Electric Corp., Buffalo, N. Y.
North Carolina	4	Mar. 21, '29	107	E. E. Kilburn	T. H. Hall	Tide Water Power Co., Wilmington, N. C.
North Texas	7	May 18, '28	170	T. D. Thomas	H. G. Mathewson	Southwestern Bell Telephone Co., Dallas, Texas
Oklahoma City	7	Feb. 16, '22	104	Ralph Randall	R. L. Jones	Southwestern Bell Telephone Co., Oklahoma City, Okla.
Philadelphia	2	Feb. 18, '03	809	G. W. Bower	A. C. Muir	1138 Commercial Trust Bldg., Philadelphia, Pa.
Pittsburgh	2	Oct. 13, '02	662	B. M. Jones	G. W. Penney	Westinghouse Electric & Mfg. Co., E. Pittsburgh, Pa.
Pittsfield	1	Mar. 25, '04	194	C. W. Germeck	W. S. Fielding	General Electric Co., 100 Woodlawn Ave., Pittsfield, Mass.
Portland	9	May 18, '09	196	C. E. Canada	A. O. Mangold	Northwestern Electric Co., 920 S.W. Sixth Ave., Portland, Ore.
Providence	1	Mar. 12, '20	100	D. W. Alden	G. E. Andrews	40 Bridgham St., Providence, R. I.
Rochester	1	Oct. 9, '14	112	R. A. Whitford	J. H. Rogers	262 Albemarle St., Rochester, N. Y.
St. Louis	7	Jan. 14, '03	361	I. T. Monseth	O. T. Farry	Wagner Electric Corp., 6400 Plymouth Ave., St. Louis, Mo.
San Diego	8	Jan. 18, '39	54	B. B. Gravitt	W. J. Kenline	3491 Cooper St., San Diego, Calif.
San Francisco	8	Dec. 23, '04	549	B. L. Robertson	G. C. Tenney	68 Post St., San Francisco, Calif.
Saskatchewan	10	Oct. 14, '25	8	M. L. Haynes	J. R. Young	1945 Scarth St., Regina, Sask, Can.
Schenectady	1	Jan. 26, '03	559	T. M. Linville	P. H. Light	General Electric Co., Central Station Dept., Schenectady, N. Y.
Seattle	9	Jan. 19, '04	230	L. D. Snow	H. M. Gustafson	7003—17th Ave., N.E., Seattle, Wash.
Sharon	2	Dec. 11, '25	153	W. L. Teague	H. S. Gates	1583 McDowell St., Sharon, Pa.
South Bend	5	Feb. 26, '41	58	J. A. Northcott, Jr.	H. E. Ellithorn	417 Parkovash Ave., South Bend, Indiana
South Carolina	4	Mar. 2, '40	53	N. H. Coit	F. W. Chapman	Water & Light Dept., Greenwood, S. C.
South Texas	7	May 23, '30	53	W. F. Pinckert	F. D. Zalmanzig	San Antonio Public Service Co., San Antonio, Texas
Spokane	9	Feb. 14, '13	82	H. J. Reeves	R. C. Kelly	Washington Water Power Co., 825 W. Trent Ave., Spokane, Wash.
Springfield	1	June 29, '22	52	Isaiah Creaser	L. P. Kongsted	American Bosch Corp., Springfield, Mass.
Syracuse	1	Aug. 12, '20	119	S. C. Osborne	M. H. Pratt	Central N. Y. Power Corp., 300 Erie Blvd., W., Syracuse, N. Y.
Toledo	2	June 3, '07	89	C. G. Brennecke	W. M. Campbell	2145 Central Grove Ave., Toledo, Ohio
Toronto	10	Sept. 30, '03	396	D. W. Callander	T. C. D. Churchill	76 Adelaide St., West, Toronto, Ont., Canada
Tulsa	7	Oct. 1, '37	87	O. A. Haas	H. A. Norberg	Nelson Electric Mfg. Co., 219 N. Detroit, Tulsa, Okla.
Urbana	5	Nov. 25, '02	78	M. A. Faucett	W. E. Miller	University of Illinois, Urbana, Ill.
Utah	9	Mar. 9, '17	64	Wm. N. Grooms	J. A. McDonald	General Electric Co., P. O. Box 779, Salt Lake City, Utah
Vancouver	10	Aug. 22, '11	95	T. Ingledow	F. V. Knight	1796 W. 15th Ave., Vancouver, B. C., Can.
Virginia	4	May 19, '22	150	C. L. Crosby	R. M. Bush	Virginia Electric & Power Co., Richmond, Va.
Washington	2	Apr. 9, '03	600	G. R. Wilhelm	F. S. Black	Potomac Electric Power Co., 10th and E Sts., N.W., Washington, D. C.
West Virginia	2	Apr. 9, '40	39	E. D. Knight	R. C. Hoffman	Appalachian Electric Power Co., Charleston, W. Va.
Wichita	7	Sept. 16, '37	57	J. F. Huff	R. F. Dice	Kansas Gas and Electric Co., Wichita, Kans.
Worcester	1	Feb. 18, '20	63	W. W. Locke, Jr.	T. H. Holton	American Steel & Wire Co., Worcester, Mass.
Total Sections	72		16,650			

OF CURRENT INTEREST

WPB Announces New Operations Plan; Names New Directors

In accord with its new concentration policy—designed to co-ordinate more effectively our military and economic objectives—the War Production Board has announced the reorganization of its administrative and operational work under new heads.

Two vice-chairmen are provided: William L. Batt, former chairman of the requirements committee, who will serve as general assistant to Chairman Donald M. Nelson and help in determining policies and directing operations; and James S. Knowlson, former director of industry operation, who will determine programs, serve as Mr. Nelson's deputy on the Combined Production and Resources Board, and be chairmen of the requirements committee.

Under the new setup, all the program development work is concentrated under Mr. Knowlson, and all the operational work—including industry and material branches, appropriate bureaus, and field organization—is brought together under Amory Houghton, director general of operations, formerly deputy chief of the bureau of industry branches. Programs and policies governing the flow of materials are worked out under Mr. Knowlson and put into operation through the operating units controlled by Mr. Houghton.

Organization of the office of operations and appointment of his principal aides was announced July 28 by Mr. Houghton. The new appointments are:

C. H. Matthiessen, Jr., former chief of the bureau of priorities, will be assistant director general for operations.

Wade T. Childress, former WPB regional director in Kansas City, will be deputy director general for field operations.

A. I. Henderson, former director of the materials division will be deputydirector general for industry operations.

J. A. Krug, former chief of the power branch, will be deputy director for priorities control.

These top assistants will act as an operations control board to advise the director general on over-all policy.

ALL OPERATING BRANCHES UNDER ONE HEAD

The placing of all of the former industry and commodity branches of the materials and industry operations divisions under Mr. Henderson's immediate direction will bring all the operating branches of the WPB under one head for the first time. Mr. Henderson will also supervise the bureau of governmental requirements, the bureau of construction, the inventory and requisitioning branch which was formerly in the bureau of priorities, and the technical services branch which was formerly in the production division.

The existing industry and commodity branches will continue to be the principal operating units. Plans for regrouping them for administrative purposes are being developed by Mr. Henderson in co-operation with John R. Kimberly and H. W. Dodge, who will be his principal assistants. Former divisional lines will be eliminated, and the work of all industry and materials branches will be co-ordinated in this single organization.

KRUG DIRECTS DISTRIBUTION OF MATERIALS

The direction and administration of priorities becomes the responsibility of Mr. Krug, as deputy director general for priorities control. He will devise and administer new, as well as existing, procedures for the distribution of materials in the war economy. He will be responsible for implementing and enforcing the programs and policies established by Mr. Knowlson, for the distribution of scarce materials to supply military, industrial, and essential civilian demands.

The production requirements plan and other devices for controlling the flow of material will be under the immediate direction of Mr. Krug. He will have as a nucleus for his organization the several branches of the former bureau of priorities except for inventory and requisitioning and the internal operations group.

Mr. Childress, as deputy director general for field operations, will supervise the regional and district offices and other field services, and will work closely with the deputies for priorities control and industry operations to carry forward the policy of reallocating the administration of War Production Board operations announced some time ago by Mr. Nelson.

SOME DIVISIONS REPORT TO HOUGHTON

A number of divisions will for the present report directly to the director general. The division of conservation; the aircraft production division which includes the aircraft, radio, and radar branches of the former production division; the tools division, which was formerly the tools branch; the shipbuilding division, which is the former shipbuilding branch; the facilities staff of the former bureau of industry branches; the division of industry advisory committees; the administrative staffs of the former divisions of production, materials and industry operations; and the internal operations staff of the former bureau of priorities.

It was also announced that the contract distribution branch of the former production division and the bureau of finance of the division of industry operations will be transferred to the Smaller War Plants Corporation.

Synthetic-Rubber Situation Clarified

In response to inquiries about the present status of the program (*EE July '42, p. 883–4*) Rubber Co-ordinator has released a letter to help clarify the situation. Essential substance of this letter follows.

"The Government is building plants based on a program for the production of synthetic rubber as follows:

700,000 Tons per year of Buna S.
60,000 Tons per year of Butyl.
40,000 Tons per year of Neoprene.

"The present program has been fixed at this amount, not because we are still searching for methods or processes but because the amount of raw material required to build plants to use any of the processes is limited and the amount allotted is all that can be spared at this time.

"Buna S, which is a general-purpose rubber, is made by a chemical combination of butadiene and styrene. Butadiene can be made from either alcohol or petroleum and many of the questions regarding the present program arise on account of this fact. Prior to the declaration of war, petroleum was chosen as the base material from which to manufacture synthetic rubber for three reasons: the more advanced experimental development of the process in this country; the substantially lower cost of production; and the apparent lack of demands for war production.

"After the declaration of war, comparative costs were not important. Rubber was essential, and speed was the first consideration. Our principal crude supply was cut off. An increased synthetic program was entered into. This program embraced all available alcohol which could be released from other war needs at that time and as more alcohol became available, because of domestic wartime measures, the proportion of alcohol to be used in the program was increased. 30 per cent of the butadiene included in the present program is being made from alcohol and most of the remainder from petroleum.

". . . . In spite of its ultimate increased cost over petroleum, the alcohol process required less strategic material for the building of new plants—that is, unless it was necessary to build a distillery to get the alcohol. However, a new and better method has been devised in the use of petroleum, and today the amount of strategic material, whether we start with petroleum or alcohol, is practically on an equal basis.

". . . . Today the program is set as we

have outlined. Tomorrow some possible improvement in process or material may appear. If we can use the new, we always will, but we cannot take on the new if to do so would slow up the program. Speed is essential."

PROGRAM EXPANDED

Shortly after Mr. Newhall's letter was issued the War Production Board approved an increase in the synthetic-rubber program from 800,000 tons to 870,000 tons. The increase will be obtained with no expenditure of critical materials for construction purposes, and is possible because of advanced engineering in the production of Butyl rubber. The new techniques permit an increase of 70,000 tons in the formerly planned 60,000-ton capacity of plants already under construction. The expanded program is not expected to alter the projected figure of 300 tons of Butyl rubber to be produced in 1942. Despite the increase, the facts on the rubber situation indicate that there is no rubber to spare for nonessential purposes.

ASA Develops War Standards

Development of standards which will save materials, make fuller use of the nation's production facilities, and make price control more effective by pegging price to quality is expected to be spurred by a contract between the Government and the American Standards Association, War Production Board Chairman Donald M. Nelson and Price Administrator Leon Henderson announced recently. According to the plan, Government funds will provide for the development by the ASA of emergency standards in connection with WPB and OPA wartime supply and price-control measures. The increasing importance of standards for pegging the price of goods to their quality has been pointed out recently in connection with the enforcement of price control. Similarly, the importance of standardization and simplification in connection with the program to concentrate civilian production (see following item) has been emphasized.

QUALITY-CONTROL

The ASA, which has been actively engaged in developing standards for war use since early in the defense program, has developed a series of three standards for quality control in mass production at the request of the War Department. The first two standards, "Guide for Quality Control (Z1.1–1941) and Control Chart Method of Analyzing Data (Z1.2–1941)" were published by the ASA in 1941, in a single pamphlet which is available at a cost of 75 cents per copy. Examples show the application of the control chart to the production of different products and deal with the blowing time of the electrical fuse; the fat content of a woolen yarn (measured as a characteristic of cleanliness); a component part of a piece of electrical apparatus inspected for conformity with four electrical characteristics; and the "spoilage" occurring in the manufacture of a bulk product—pile floor covering.

A third American War Standard recently issued is the "Control Chart Method of Controlling Quality During Production (Z1.3–1942)," selling at 75 cents per copy. This standard is intended to show the manufacturer how he can keep track of his production process by means of a quality-control chart which carries a pair of control limits and which serves as a criterion in determining whether the production process is running smoothly. The control limits are computed from quality measurements made on a number of samples of the product.

MACHINE-TOOL ELECTRICAL STANDARDS

The ASA recently announced the completion of another American War Standard, "Machine Tool Electrical Standards (C74–1942)." The pamphlet is available at 40 cents per copy. The purpose of this standard is to speed the manufacture of machine tools by standardizing the electrical wiring of such tools. It has already been made mandatory by an order of the WPB which limits the future electrification of machine tools to the types of equipment recommended in this standard.

Each of the above American Standards may be obtained direct from ASA, 29 West 39th Street, New York, N. Y.

WPB Orders Concentration of Civilian Industries

Donald M. Nelson announced recently that the War Production Board has approved the principle of concentration of industry as a means of alleviating the strain placed on the civilian economy by the war effort. In approving this principle, the board also approved certain broad policies governing the way in which concentration will be made effective.

SELECTIVE LIMITATION

Heretofore, Mr. Nelson pointed out, the necessary limitation of output of civilian industries has been attained for the most part through orders which impose uniform percentage reductions on all firms. These orders, which could be drafted and applied quickly and were necessary as a first step, have resulted in large savings of critical materials and have facilitated conversion to war production.

The war program has now reached a stage, however, in which the imposition of straight percentage cuts on all firms does not provide for the most effective use of the nation's resources. Consequently, Mr. Nelson said, the board has decided that wherever possible a policy of selective limitation be applied, with essential civilian production concentrated in certain plants and regions.

CONDITIONS FOR CONCENTRATION

In adopting this policy, the board held that there is a strong prima facie case for concentrating the production of civilian goods wherever one or more of the following conditions are found in a civilian industry:

1. Some or all firms in the industry are needed for war production and can be converted to such production.

2. Permitted civilian production is so restricted that economic operation of all firms in the industry is not possible.

3. A significant part of the production is continuing in areas where there are bottlenecks in labor, transport, power, or warehouse facilities.

It is the belief of the board that one or more of these conditions applies to a very large part of civilian industry, and it was agreed that a study should be made at once of the effect upon industry of the curtailment and limitation orders thus far issued.

SMALL PLANTS MAY CONTINUE

No hard-and-fast rules can be laid down, Mr. Nelson said, to govern the selection of "nucleus plants"—plants which will be allowed to continue operation at or near capacity. In general, however, he said, the following criteria will guide WPB officials in such selections:

1. As a rule, small plants will be kept in civilian production, and large plants, which are usually better equipped to handle war contracts, will be required to suspend civilian production.

2. Civilian production should be suspended in areas where labor is urgently needed in war plants.

SEEK TO AVOID POSTWAR MONOPOLY

Mr. Nelson said the board fully realizes that concentration of civilian production raises many difficult problems—compensation to closed-down firms, maintenance of trade marks, and rearrangement of distributive channels. But while these are of great importance to the individual firms involved, he said, from the standpoint of war production they are secondary to the need for determining the degree of curtailment, concentrating production, and converting nonnucleus firms to war work. In working out concentration plans, the board feels that these principles should be applied:

1. Concentration plans should not foster postwar domination of an industry by one or a few companies. A plan which will make possible the re-entry of the largest number of firms into the industry after the war should be given preference, so long as it is consistent with efficient prosecution of the war.

2. Wherever possible, concentration plans should be accompanied by standardization and simplification of the product.

3. Concentration programs should be drafted for limited periods—with one year, probably, as a maximum—and should be flexible enough so that they can be revised if circumstances change.

4. A concentration program for any industry should be co-ordinated with any program which the Office of Price Administration may work out for concentration of the distributive channels of that industry.

5. Where compensation is provided for firms closed down, it should be paid by the firms which continue operations and should be limited to the duration of the concentration program.

Civilian Radio Instructors Needed by Army Air Force

The United States Army Air Force has announced that thousands of civilian radio instructors will be needed to train tens of thousands of enlisted men in the theory and technique of radio operation, according to a report by the Civil Service Commission.

To qualify for a position as radio instructor, an applicant must have either one year of technical radio experience or two years of college study which has included a certain amount of mathematics and physics. Radio men in defense plants will not be considered.

Men chosen for these positions will be given special training. Positions are open for student instructors at $1,620 per year. Upon successful completion of the training course (usually 3 months) student instructors may be promoted to the position of junior instructor at $2,000 per year. Inquiries for further information should be addressed to the Seventh United States Civil Service District, Office of the District Manager, Room 1120, New Post Office Building, Chicago, Ill. Openings are in the states of Illinois, Wisconsin, North Dakota, and Florida.

Educators Consider Relations Between War and Colleges

A conference of officers of institutions and organizations of higher learning was held July 15–16, 1942, at Baltimore, Md., to consider relationships between the war effort and the institutions of higher education—universities, schools of technology, colleges, and junior colleges. During the conference a statement outlining these relationships was drawn up by a working group of approximately 75 officers from various types of institutions, which subsequently was adopted by the conference.

At a similar conference held in Baltimore, January 3–4, 1942 (*EE Jan. '42, p. 77–2*) the institutions of higher education of the country pledged their total resources to the winning of the war and urged prompt development of plans providing for "a continuous and adequate supply of men and women trained in technical and professional skills and in leadership to meet both immediate and long-range needs." The July conference reaffirmed the declarations of the January conference in addition to issuing the foregoing statement, which the American Council on Education has termed "one of the most important pronouncements which have been made by representatives of higher education during this war." Full text of the statement follows:

"1. We deplore the continuing lack of any adequate, co-ordinated plan for the most effective utilization of higher education toward the winning of the war, and we urge the establishment of such a co-ordinated plan at the earliest possible moment.

"2. The government is not utilizing the institutions of higher education to capacity and is, therefore, impeding the flow of highly trained manpower essential to victory in a long war.

"3. Through the provision of year-round instruction and many other recently adopted changes, higher education has demonstrated its readiness to devote all its facilities and energies to the war effort. However, the lack of any adequate, co-ordinated plan has given rise to widespread confusion among governmental agencies, educators, students, and the general public. This confusion constitutes a serious barrier to the full wartime utilization of higher education and hence to the successful prosecution of the war.

"4. We believe that the full utilization of higher education is essential to the winning of a long total war because:

"*a.* The war can be won only if a continuous flow of highly trained manpower is prepared for participation in the war effort.

"*b.* The institutions of higher education are the only institutions staffed and equipped to provide many essential types of advanced training.

"5. To insure more effective utilization of the facilities of higher education through the establishment of a co-ordinated plan, we recommend to the Secretary of War, the Secretary of the Navy, the Director of Selective Service System, and the chairman of the War Manpower Commission that immediate steps be taken to assure effective and continuing co-operation between the agencies they represent and higher education.

"6. Among the premises upon which such a co-ordinated plan should be based are the following:

"*a.* The function of higher education is to provide the nation with broadly educated and highly trained men and women. This permanent function must be continuously performed lest the health, safety, and welfare of the nation be endangered; but in the present grave crisis, the winning of the war must have right of way in higher education as well as in all other national undertakings.

"*b.* To develop breadth of understanding, stamina, and qualities of leadership is a major function of higher education. These are essential characteristics of good officers in the armed forces. It is significant that although only 12 per cent of the men already inducted into Selective Service have had college training, 80 per cent of the men selected for officer training in the Army have been chosen from this group of college men.

"*c.* The year-round instruction which has been established by colleges and universities to serve the war effort creates new financial problems for students. Present plans for the voluntary enlistment and training of college students provide only for those young men who can finance a college education or who can secure assistance within existing financial-aid programs. Large numbers of qualified young men are therefore barred from special types of training. Such a situation limits the supply of broadly educated officer material and denies to many young men equal opportunity for training. Economic status, race, or creed should not be allowed to restrict the training of adequate, skilled manpower at the college level for the war program.

"*d.* Present plans for the enlistment and training of college students are inadequate also because (1) they fail to provide clearly defined avenues of training and service for those male students who are physically unqualified for military service but who are intellectually fitted to contribute to the winning of the war through industrial and other civilian pursuits, and (2) they fail to include women, who, as shown in other countries, have a vital part to play in the national effort.

"*e.* The institutions of higher education stand ready to make such further adaptations of their programs and facilities as may be necessary to meet the objectives set up by the Federal agencies concerned with the training of college students for war service.

"7. The proposed co-ordinated wartime plan for higher education should be established at once so that with the opening of the fall terms in 1942 the institutions of higher education of the country can throw their entire resources into the war effort.

"8. We recommend that the American Council on Education, which was established during the First World War to represent all the organizations of higher education, be recognized as the appropriate nongovernmental agency to take such steps as may be necessary to implement the proposals herein stated and to serve in a continuous capacity for facilitating co-operation between higher education and government."

Additional Information on Army Specialist Corps

As supplementary material to the talk on the Army Specialist Corps by Brigadier General William O. Hotchkiss, reported in the August issue of *Electrical Engineering*, pages 440–2, the following information may be of interest.

Appointments to the Army Specialist Corps will be made for the duration of the War and six months thereafter. Appointments for a lesser period may be made under exceptional circumstances at the discretion of the Director General. There will be two classes of personnel, officers and specialists, who will have relative rank with officers and enlisted men of the Army. In general, their titles will be the same as those for corresponding rank in the Army. Promotions may be made by the Director General. Decorations authorized by law may be awarded by the Secretary of War upon the recommendation of the Director General. The Army Specialist Corps uniform will be practically the same as that of the officers and enlisted men, respectively, of the Army. Both uniform and insignia will be distinctive so that members of the corps will be readily recognized as such.

The rate of pay for members of the corps is based upon the Civil Service Classification Act and will, in general, be comparable to that in use for similar grades in the Army. Any person occupying a Government position other than temporary may be transferred or appointed to the corps and shall during the period of employment therein be deemed to be on leave of absence without pay. Individuals appointed to the Corps will not acquire Civil Service status, but all appointments for the duration are subject to the Civil Service retirement deductions.

Members of the corps will exercise administrative and supervisory functions only. They will not exercise command functions in so far as Army officers or enlisted men are concerned, except that when Army personnel are assigned to duty in any activity operated by officers of the Corps, they will be subject to the orders of the officers to the same extent and in the same manner as though they were members of the Corps.

Selective Service Broadens Technical-Student Deferments

Emphasizing the necessity of maintaining the potential supply of men in scientific and specialized fields through continuing their education in college and their employment in the fields for which they have been selected for deferment, Occupational Bulletin No. 10, issued recently by Selective Service, is considered by the American Council on Education to be one of the most important yet published dealing with students.

The bulletin includes consideration for occupational deferment of selected graduate students and provides for a 60-day period for deferment beyond graduation. It specifies the following fields in which shortages of personnel exist: accounting; chemistry; economics; aeronautical engineering; automotive engineering; chemical engineering; civil engineering; electrical engineering; heating, ventilating, refrigerating, and air-conditioning engineering; marine engineering; mechanical engineering; mining and metallurgical engineering; radio engineering; safety engineering; air, highway, railroad, and water transportation engineering; geophysics; industrial management; mathematics; meteorology; naval architecture; personnel administration; physics; astronomy; psychology; and statistics.

As changes in personnel needs modify the fields in which there are shortages, this list probably will be revised. The inclusion of some of the more general fields will require even more careful appraisal of the students' ability and vocational purpose in order to select those for whom the college will request occupational classification.

A graduate or postgraduate student who is pursuing additional studies for these scientific and specialized fields, may be considered for occupational classification if he is also engaged as a graduate assistant in the instruction of undergraduate students in these fields, or if he is engaged in scientific research related to the war effort which is supervised by a recognized Federal agency.

Holders of degrees in these fields, continuing the deferment already granted them as necessary men to complete their training, will be deferred for an additional 60 days beyond graduation, in order that they gain time to be placed among the skilled personnel in their essential activity.

Priority System Described. A pamphlet called "How the New Priority System Works" has recently been issued by the Research Institute of America, analyzing the revised governmental production-requirements plan. Directed to the attention of business executives so that they may learn how to present a clear and convincing picture of their inventory, requirements, production schedule, priority pattern, and importance in the war picture, the analysis aims at an effective understanding and prosecution of the war program. Copies may be obtained at a price of $2 from the Research Institute of America, 292 Madison Avenue, New York, N. Y.

New Radio Series Announced by Publishers

A new series of technical books in the field of radio communication engineering, to be prepared under the consulting editorship of Beverly Dudley, acting managing editor of *Electronics* has been announced by the McGraw-Hill Book Company of New York, N. Y. To be known as the Radio Communication Series, these forthcoming books are intended to provide a co-ordinated and uniform group of texts of collegiate caliber covering all phases of modern radio communication, to serve the student of communication engineering as well as to serve as reference material for the practicing engineer. With the present military interest in and need for trained men in the field of radio communication, the launching of this new series comes at a propitious time. As originally outlined, the series calls for individual texts on:

1. Basic Mathematics for Communication Engineers
2. Principles of Electricity
3. Introduction to Radio Engineering *
4. Fundamentals of Electric Circuits
5. Electrical Filters
6. Transmission Lines and Wave Guides *
7. Antennas and Radiation Phenomena
8. Electron Tubes in Communication
9. Frequency Modulation *
10. Ultrahigh Frequency Technique
11. Acoustics and Electromechanical Devices
12. Communication Measurements

* These books are already in preparation.

Women Fill Technical Positions

To replace male engineers lost to the company through selective service or enlistment in the armed forces, the General Electric Company is hiring 150 young college women in a technical status. The first 22 of the group are now at work, and this number will be supplemented each week until the quota is reached. The girls are being given the company's well-known test engineering course, and in the fall will take classroom courses in the fundamentals of engineering and company organization. The work the girls are now doing is considered elementary, and they are shifted from department to department in an orientation course. Work they will do includes figuring computations, charting graphs, and calibrating fine instruments for use in the machine-tool industry.

Applicants selected for the course must have majored in either mathematics or

"Jumbo Luminaires" Provide Diffused Light

Designed to provide diffused lighting, especially for war plants working with polished metal sheets which tend to reflect glare, this light fixture was developed in the lamp department of the General Electric Company, Cleveland, Ohio. It contains a 3,000-watt mercury tube, which is shown between eight 200-watt inside-frosted filament lamps, and produces approximately 150,000 lumens. The unit, measuring eight feet in length by four feet in width is constructed of fiberboard, thus saving critical metal commonly used in industrial fixtures.

physics in college and have had minor training in the other. Their mathematical training must include courses through calculus.

Engineers Now Being Hired by U. S. Employment Service

The War Manpower Commission has requested firms doing war work to hire all their engineers and other executives through the United States Employment Service. Positions available will be filled from the National Roster of Scientific and Specialized Personnel, to which names are constantly being added, including those obtained from Selective Service occupational questionnaires. Engineers who consider themselves available for war jobs are urged to see that their names and records are on the roster.

According to Richard C. Brockway, director of USES for New York State, the New York professional office has filled more than 150 positions paying $3,000 a year or more during one recent month—including positions as structural engineers, controller for a chemical construction company, an architectural designer, industrial engineers, and personnel executives.

Airplane Engines Produce Power During Break-in Tests

New airplane engines which once did no useful work during break-in runs have now been harnessed to produce electric power during the testing period. The new power-producing method has been achieved by connecting the airplane engines to ordinary generators of the type long used in Diesel-electric power plants, which "feed back" into the plant electric-supply system.

Airplanes, unlike automobiles, may not be broken in by slow driving, but must be ready to run at full speed on the initial take-off, which requires more power than actual flying. During the 12 hours usually required to break in an airplane engine, great quantities of high-octane gasoline are consumed—gasoline which under the old method, utilizing a propeller as the load, was dissipated in churning the air. The new process feeds back about 2,000 kilowatt-hours during the test run of one large engine.

The engine being tested is connected by a flexible-shaft coupling to a magnetic coupling, which transmits power to a synchronous generator. In operation, this unit, working as a synchronous motor, is brought up to speed, and the coupling is energized just enough to crank the engine slowly. When the engine fires, the coupling is de-energized, and the motor cut off the line. After the engine is brought up to speed, the coupling can again be energized. The synchronous machine then operates as a current-absorption-type dynamometer, generating power which is fed back into the line.

Recently, however, a more flexible power-recovery system eliminating the coupling device has been developed. This system incorporates the characteristics of the coupling and the constant-speed generator in one variable-speed unit.

End-Product Designations to Aid Critical Materials Allocation

As the supply of basic materials for the war program and related civilian economy is not large enough to satisfy all essential requirements, it is necessary to review the most essential requirements of finished products and determine their urgency of manufacture. To this end, a standard method of identification and reporting has been established by the War Production Board for all industry.

The method of identification consists of a dual system of letters and numbers, letters indicating broad classes of ultimate purchasers and numbers indicating the classes and subclasses into which certain industries have been grouped. Effective August 31, 1942, all orders for critical materials must carry such identification. Neither the code number nor letter indicates the order of importance, but merely serves to indicate the purpose for which any particular product or material will be used. The system thus will aid in the effective scheduling of the flow of materials in our war program.

As an example, a manufacturer of typewriters for use by the Army would designate orders for raw materials with the code identification *A*-19.00; if for the Navy, *N*-19.00; and if for other use, *X*-19.00. (*A*, *N*, and *X* designate use of the end-product by the Army, Navy, and others, respectively, and 19.00 is the code number for manufacturers of equipment and supplies for office use.) Full details of the system and how to apply it are covered in a booklet "Priorities Regulation No. 10" which can be obtained from the War Production Board, Division of Industry Operations, Washington, D. C.

New WPB Power Branch Head. Herbert S. Marks, assistant general counsel of the War Production Board, has been appointed acting director of the WPB Power Branch, filling the vacancy caused by the appointment of J. A. Krug, former chief of the Power Branch, as deputy director general for Priorities Control. Mr. Marks continues as assistant general counsel of WPB, which office he has held since April 1941, and advances from the office in which he served since the creation of the Branch in July 1941. He came to the Office of Production Management, predecessor of WPB, from the staff of the Trustees of the Associated Gas and Electric Corporation. Earlier he was general counsel of the Bonneville Power Administration and assistant general counsel of the Tennessee Valley Authority. He is a native of Danville, Pa., and a graduate of the University of Pennsylvania and of the Harvard Law School.

War Plants Urged to Use Production-Drive Aids

The war-production drive inaugurated last March by Donald M. Nelson, chairman of the War Production Board called upon labor and management to form joint committees to aid manufacturers in meeting the vast production requirements for the war effort. The WPB reports that production is approaching goals set by the president six months ago as a direct consequence of the co-operation of labor and management plus the service rendered by the War Production Drive Headquarters which is a WPB agency. However, a survey has disclosed that there are still a large number of plants in which these labor-management committees have not reported to the War Production Drive Headquarters and which consequently are not receiving the production aids and services made available by the WPB. Other plants, it is believed, have not yet established production drives.

Among the material and services supplied to all labor-management committees in war-production plants are the following:

Stickers
Posters
Streamers
Booklets and leaflets for information stands
Motion pictures
Transcription service for plants with loud speakers
Bulletin board placard service
Material for plant newspapers
Information exchange reporting the progress of the drive
Awards
Booklets of plans for production drives

Labor-management committees not receiving the above aids and those interested in organizing war-production drives are invited to communicate at once with the War Production Drive Headquarters, War Production Board, Washington, D. C.

OTHER SOCIETIES •

National Safety Executive Named; Program Expanded

N. H. Dearborn, dean of the division of general education of New York (N. Y.) University, has been appointed executive vice-president and managing director of the National Safety Council. He will actively direct the greatly expanded wartime program, which is being conducted by the Council and which is intended to cover every phase of accident prevention. (*EE, Oct., '41, p. 510–11; Apr. '42, p. 221–2.*)

Funds necessary for this enlarged program, which aims to stop accidents which are impeding war production and delaying victory, are being obtained now from commerce and industry by the Council's War Production Fund to Conserve Manpower. Local safety councils will be given assistance by direct allocation of funds needed to amplify their present programs and by additional personnel for industrial and public safety. It is planned to establish

local safety councils in war production areas where none now exist, in recognition of added safety hazards caused by the migration and concentration of population in these areas. It is further planned to aid plant management in strengthening plant safety programs so that safety precautions will be impressed upon the worker as a necessity in the plant, in the home, and in every activity.

IES Announces New Officers

The Illuminating Engineering Society recently announced new officers for 1942–43 as follows:

President: R. B. Brown, Jr., illuminating engineer, Boston (Mass.) Edison Company

Vice-President (term ending September 30, 1944): S. B. Williams (M'37) editor, *Electrical World*, New York, N. Y.

General secretary: O. P. Cleaver (A'36) head of the illumination section, commercial engineering department, Westinghouse Lamp Division, Bloomfield, N. J.

Treasurer: A. F. Wakefield, F. W. Wakefield Brass Company, Vermilion, Ohio

Directors (term ending September 30, 1944): A. A. Brainerd, Philadelphia (Pa.) Electric Company; R. W. Staud, Benjamin Electric Manufacturing Company, Des Plaines, Ill.

Regional vice-presidents (term ending September 30, 1944): I. L. Illin G. Wisconsin Electric Power Company, Milwaukee, representing the mid-western region; G. R. Baumgartner, General Electric Company, Nela Park, Cleveland, Ohio, representing the Great Lakes region; Fred J. Wellhouse, Westinghouse Electric and Manufacturing Company, San Francisco, Calif., representing the Pacific Coast region; Clarence C. Keller, Holophane Company, Inc., New York, N. Y., representing the northeastern region; and J. M. Guillory, industrial and commercial engineering division, New Orleans (La.) Public Service, Inc., representing the southern region.

Future Meetings of Other Societies

American Institute of Chemical Engineers. 35th annual meeting, November 16–18, 1942, Cincinnati, Ohio.

American Institute of Mining and Metallurgical Engineers. Regional meeting, October 12–17, 1942, Los Angeles, Calif.; joint meeting, coal division, AIME, and fuel division, ASME, October 1–2, 1942, St. Louis, Mo.

American Physical Society. 251st meeting, November 27–28, 1942, Chicago, Ill.

American Society of Mechanical Engineers. Fall meeting, October 12–14, 1942, Rochester, N. Y.; annual meeting, November 30–December 4, 1942, New York, N. Y.

American Society of Tool Engineers. Semiannual meeting, October 16–17, 1942, Springfield, Mass.

American Welding Society. 23d annual meeting, October 12–15, 1942, Detroit, Mich.

Association of Iron and Steel Engineers. Annual convention, September 22–24, 1942, Pittsburgh, Pa.

Electrochemical Society. Fall meeting, October 7–10, 1942, Detroit, Mich.

Illuminating Engineering Society. Annual convention, September 21–22, 1942, St. Louis, Mo.

National Electrical Manufacturers Association. Annual meeting, October 26–30, 1942, New York, N. Y.

National Safety Council. 31st national safety congress and exposition, October 27–29, 1942, Chicago, Ill.

INDUSTRY . . . . .

More Generating Units for Government Plants

More than a million kilowatts of hydroelectric power will be added to the nation's supply by July 1944 at five Bureau of Reclamation multipurpose irrigation projects in the West, according to a recent announcement, as a result of higher priorities granted recently by the War Production Board for Reclamation dams, powerhouses, and generating equipment. The additions will bring the total operating capacity of Reclamation power plants in 12 states to $2^1/_2$ million kilowatts. The potential annual output will be more than 20 billion kilowatt-hours.

The highest priorities assigned—*AA*-3—were allotted to the following installations:

Four generators, 30,000 kw each, at Parker Dam. The first generator was scheduled to go into action in August, the second in September, the third in October, and the fourth in May 1943.

Two 75,000-kw generators at Grand Coulee Dam, scheduled to start operating in November this year. These two machines were originally ordered for Shasta Dam but were shifted to make their output available to war industry a year sooner.

An 82,500-kw generator (*A*-5) at Boulder Dam, in December.

The following units were assigned *AA*-4 ratings:

Green Mountain Dam, Colorado Big-Thompson project, Colorado—providing 21,600 kw (two generators of 10,800-kw capacity) in February and March 1943.

Grand Coulee Dam, Washington—three generators of 108,000 kw each (*L*-4, 5, and 6), scheduled for July, September, and November 1943, bringing the total capacity of the Grand Coulee plant to 818,000 kw—second only to Boulder Dam in size.

Boulder Dam, Arizona-Nevada—generators *N*-7, capacity 82,500 kw, scheduled for December 1943 (bringing the total installed capacity at this largest power plant in the world to 1,032,000 kw).

Shasta and Keswick Dams, Central Valley projects, Calif.—two big generators of 75,000 kw each at Shasta by January 1944 and another in March; two generators of 25,000 kw each at Keswick in May and June 1944.

October 4–10 Designated Fire Prevention Week

With the issuance of a proclamation by President Roosevelt, designating the week of October 4 to 10, 1942, as Fire Prevention Week, plans are being made for bringing about the widest and most effective observance of the event this year since President Woodrow Wilson in 1920 issued the first Fire Prevention Week proclamation. President Roosevelt, in his proclamation, called upon the people of the United States to give special heed to the importance of taking active measures to conserve human and material resources from fire. At the same time, he directed the Office of Civilian Defense and other Federal units to initiate programs for stressing the importance of attaining the objectives sought in the fire-prevention effort. State and local governments and other agencies also were asked to promote observance.

In 1941 the national fire loss amounted to $304,000,000 and for the first six months of this year the loss approached $171,000,000 or four per cent greater than the comparable period in 1941. Every year fire takes a toll of 10,000 lives throughout the United States and a very much larger number of people are injured by fire. In the first six months of 1942 there were 38 large fires in the United States, each involving an estimated loss of $250,000 or more, many of which were in war-production plants or in essential wartime facilities such as warehouses, ships, and piers. But in some cases even small fires occurring in plants under subcontract, making some essential part for large airplanes or other implements of war, have held up assembly lines of large war-production factories.

In this critical year, when every fire diverts material and manpower from decisive war production, interrupts and impedes the war program, and in many cases destroys vital materials and facilities that cannot be replaced during the present emergency, it is especially important that all public and private organizations join together in an intensive effort to eliminate fire hazards and to take essential steps for fire protection.

Photographic Exposure Computer. Photographic exposures for all types of negative films in land, marine, and aerial photography, for any location in the world and for a wide variety of light conditions can be determined from the photographic exposure computer issued recently by the American Standards Association. Designated "American Emergency Standard" (Z38.2.2–1942), the computer originally was prepared for use by the photographic divisions of the armed services. The present edition is identical with the original, except for lighter weight binding and the stock on which it is printed. The computer is pocket size ($3^1/_4$ by 5 inches) and contains 24 pages printed on lightweight durable cardboard. It includes light index tables for various latitudes, scene index tables for different types of scenes under various light conditions, and a simple exposure calculator which gives the final result—all supplemented by appropriate explanatory material. An appendix covers exposures under unusual conditions and exposures with the use of photoflash and photoflood lamps. The computer may be obtained at a cost of $1 from ASA, 29 West 39th Street, New York, N. Y.

1942 National Power Show. The 15th National Exposition of Power and Mechanical Engineering scheduled for Grand Central Palace, November 30 to December 5, 1942, is being planned this year as a direct aid to war production. The exhibits should be of interest to engineers and operating men who are faced with many new production and maintenance problems, as well as to men with many industrial responsibilities. The displays will include insulation, combustion controls, engineering supplies, electrical equipment, power transmission and material handling products, and a complete line of tools for various production and maintenance uses.

EDUCATION . . .

Federal Loans to Aid Students in Technical Courses

A loan fund of $5,000,000 has been voted by Congress and will soon be available to help college students speed up their training for technical and professional jobs. Monthly loans totalling not more than $500 a year, at 2½ per cent interest annually, and cancelled if the student is drafted during training, will be made directly to students by colleges and universities, and by public or college-connected agencies. Federal funds will be allocated to the loaning institutions by the United States Office of Education on the submission of estimates of the amount of money for such loans.

This financial assistance will permit students to pursue intensive programs of study which will prepare them as soon as possible to meet the growing need for technicians. Loans are available only to students whose technical or professional education can be completed within two years, in the fields of engineering, physics, chemistry, medicine (including veterinary), dentistry, and pharmacy.

The student agrees in writing: (1) to participate, until otherwise directed by the chairman of the War Manpower Commission, in accelerated programs of study in any of the authorized fields; and (2) to engage for the duration of the wars in which the United States is now engaged, in such employment or service as may be assigned by officers or agencies designated by the chairman of the commission.

The maintenance of satisfactory standards of scholarship and the actual need of assistance will be added factors in determining the eligibility of the students to be awarded the loans, and these loans will be evidenced by notes executed by student borrowers payable to the Treasurer of the United States.

Science Series Planned. A series of books on science to be issued under the title, "Treasury of Science," and to be edited by a board including professors in scientific fields, is planned for publication by the L. B. Fischer Publishing Corporation, New York, N. Y. The series is to consist of a number of pocket-size books, selling at $1.25, and is designed to serve as a source of introductory information on various aspects of modern scientific knowledge for students and the general public. AIEE members are invited by the publishers to submit manuscripts on scientific subjects, which should be sent direct to the publishing company.

Expansion of Facilities at Cooper Union. The completion of new facilities for laboratory instruction in communication subjects of the day and evening courses at Cooper Union was announced recently by Norman L. Towle (A'20, M'24), head of the department of electrical engineering. Day and evening curricula in electrical engineering now include subjects in power or communication specialization, available to the student on an option basis. Instructional procedures have been developed and revised to standards commensurate with optional specialization at a senior level, and the recently acquired communication equipment will extend the range of fundamental electrical measurements that may be made to frequencies above the television band. The new apparatus, includes an impedance bridge, a 9-inch oscilloscope, standard, square-wave, and video-signal generators, oscillators, and a wave analyzer.

LETTERS TO THE EDITOR

INSTITUTE members and subscribers are invited to contribute to these columns expressions of opinion dealing with published articles, technical papers, or other subjects of general professional interest. While endeavoring to publish as many letters as possible, Electrical Engineering reserves the right to publish them in whole or in part or to reject them entirely. Statements in letters are expressly understood to be made by the writers, publication here in no wise constitutes endorsement or recognition by the AIEE. All letters submitted for publication should be typewritten, double-spaced, not carbon copies. Any illustrations should be submitted in duplicate, one copy an inked drawing without lettering, the other lettered. Captions should be supplied for all illustrations.

Writing a Technical Paper

To the Editor:

The initial start in the preparation of either a paper or an address is something to say. Substance rates higher than form, with men whose professional lives depend on results, and accurately stated fact stands ahead of empty polished English. Although adequate presentation is essential, mastery of English will not take the place of facts worth telling. Attempts to bolster mediocre investigations with long-winded reports bring to mind Lincoln's comment on one of McClellan's reports. The President, who wanted results, replaced the fluent general.

The first requirement of clear writing is clear thinking. A fountain cannot rise higher than its source, and neither can mud-puddle thinking produce spring-water writing. All too frequently, getting a clear style will require a potential author to revise if not indeed to recast his methods of thought as well as his sentences.

The prime requirement for logical writing is logical thinking. The way some authors wander through their writings suggests a dim path in dense woods, the kind of path that before long disappears altogether. With a few persons, a faulty Mendelian inheritance or perhaps an unsuspected birth injury is the cause. A competent editor may be the only help that such unfortunates can have. Yet, as a rule, meandering of this type comes from mental inertia, which means that meandering authors can correct their defect any time that they become willing to make the necessary effort.

Writing logically includes paying proper attention to perspective. Obtaining perspective in writing requires a comprehensive knowledge of the subject and also a willingness to write for the audience instead of for the author. A mass of minute detail and excessive attention to some one phase may satisfy the author's vanity or personal interest, yet such presentation never gives the audience the balanced ration that normal persons want.

"Brevity is the soul of wit," and conciseness in an article intended for mature minds is a virtue. A reviewer thinks that my present not-inconsiderable paring of this 1,900-word letter is enough. He may be wrong, because such a question must remain a matter of judgment, yet even a virtue can be overdone. The person who reads a paper is doing the author a favor, and the author should take account of that fact. A brevity too great for ease in reading is no better than excessive length.

For some centuries a man was not considered learned unless he wrote in Latin. In the days when good modern-language dictionaries had not yet been born, this attitude was perhaps excusable, despite its source. One of the chief hangovers remaining from this old notion is the circumlocution of the third person passive, which ponderous, pompous, and other unskilled authors affect. Although the passive, like strychnine, has legitimate use, too much of the stuff turns it from a tonic to a poison. To be consistent, a good engineer, who is a man of action, should write in the active voice. If every engineer did so, perhaps we should hear less often the comment, "They say what they don't mean, and mean what they don't say." Life is short; need I list the other professions that call forth the same comment?

Years ago a certain one-horse college looked down on a tiny farmers' center that consisted chiefly of a single unshaded street, which formed an inexhaustible source of dust in the summer and of mud in the winter. A new instructor at the college, wanting a patch or two on his shoes, could see no way to get the pair to the town cobbler other than to float them himself down the town's river of dust. Torn woefully by the horns of need and desire, the fledgling called on the college president to ask if it would be in keeping with the dignity of an instructor in that great university to be seen on Main Street carrying a pair of worn shoes. Today, thanks in large measure to that president, who did not take himself too seriously, the former rural collegette has become a university of some standing. The reply of this president met the situa-

tion: "Young man, if you have only a little dignity, you had best take good care of what you have." Many a stilted, obscurely worded paper has reminded me of this story. A fully qualified writer of good taste never has to worry about dignity.

Inadequate preparation is a fault all too common. One remedy is to make an outline of the points the article should cover, checking their order carefully, and then to tell the story to a boy in his middle 'teens. Unless such a story deals with highly abstract matter, if the boy cannot understand it, then there is something wrong with both the material and its telling. If a second and a third attempt, each time with a new boy and additional preparation, do not bring better results, write out a draft, let it sleep for a time, and then start all over.

The best critic of my own writings, a cultured gentleman, was so well qualified that he never felt obliged to remind me that he had an advanced degree and a position of authority. Because he was as honest as a piece of plate glass I was always able to evaluate his comments for my audiences. Equipped with courage rather than conceit, he never feared to tell me that he did not understand something, and to suggest that I clarify. Such a critic, as rare as a precious jewel, is worth hogsheadsful of flattering wives and friends, and boatloads of bluffers. Nevertheless, a critic who finds fault for the sake of finding fault is hardly better than a backpatter.

Woolley and Scott's "College Handbook of Composition," among other virtues, has the somewhat unusual merit of keeping to its subject; it actually practices what it preaches. Yet my experience has been that any such book, in the hands of a beginning author, leads the author to spend time and effort in quibbling over inconsequential matters and in arguing—"argufying" is really a more appropriate word here—over sentences that an experienced author would recast instead of defending. Rather than such a manual, despite its value to both a student and a seasoned author, I recommend close study of a carefully edited nontechnical journal, such as *Newsweek* or *Time*.

When a diamond cutter has done his job properly, a polisher can easily finish the gem. In the same way, if an article is roughhewn correctly, a qualified editor will finish the work in a short time. Yet even the best editor cannot put enough polish on a piece of shale to make it worth carrying away; the author must supply diamonds if he wishes the editor to bring out a diamond finish.

Omnipotence in every field of human endeavor is reserved for Hitler alone, not for a mere editor. Perspiration will never taken the place of inspiration; yet inspiration without perspiration rarely gets results of value. For these reasons an author should himself expect to do a fair part of the total work required to produce a good manuscript, not leaving too much for even the most willing and qualified editor.

My Anglo-Saxon vocabulary, with its short, simple words, must have come from my boyhood reading and rereading of Sir Walter Scott and others like him. Each of three modern languages has been of value to me in my study of English. On my second attempt I succeeded in breaking the preservative ice around Latin enough to start dissecting the cadaver. The chief gain for myself is the knowledge that Spanish is live Latin, and the opinion that Spanish, when taught logically, has a far higher value for most Americans than dead Latin. Seneca, for example, was a Spaniard; educated Spaniards took over the Roman senate when Rome had gone far toward decay. Perhaps Spain's help also was too little and too late.

A lifelong reading of good writings has given me my knowledge of what good writing is; Hawthorne, Kipling, Poe, Stevenson, and Tennyson are examples of my favorite authors. Henty and his stereotyped hack work, unknown today, showed me many things to avoid. My practice in writing began with letter writing, and continued with laborious correction of draft after draft of formal work. Without going into details, let me say that whatever command of English I may have has come from efforts that had little or nothing to do with classroom work. What I have done in self-instruction others can do also.

This little article is a summary. For such an abstract, a comparatively large proportion of short paragraphs is permissible. In general, however, a short paragraph should be reserved to relieve long paragraphs, or for force. An attempt to obtain either force or clarity by a series of paragraphs of only one or two sentences means that the author does not think connectedly, and the result is a choppiness and lack of organization that grates on a lover of good English. "An equal emphasis on all is no emphasis at all." Paragraph an article by topics, not with a ruler. Use a ruler merely to make sure that no paragraph is overly long. A sufficiently liberal use of headings will help to point out the progression that a reliable author wishes to make in every article, yet nothing will take the place of proper paragraphing. Only good paragraphing allows unity and cohesion.

Choppy sentences are as bad as choppy paragraphs. Although necessary in a story for small children, they prevent subordination of detail, so that reading a string of them is like riding over cobblestones or washboarding. Longer sentences, with subordinate parts for subordinate matters, present a clearer and more faithful picture; they permit perspective. Sentences make paragraphs, and paragraphs make an article—or break it.

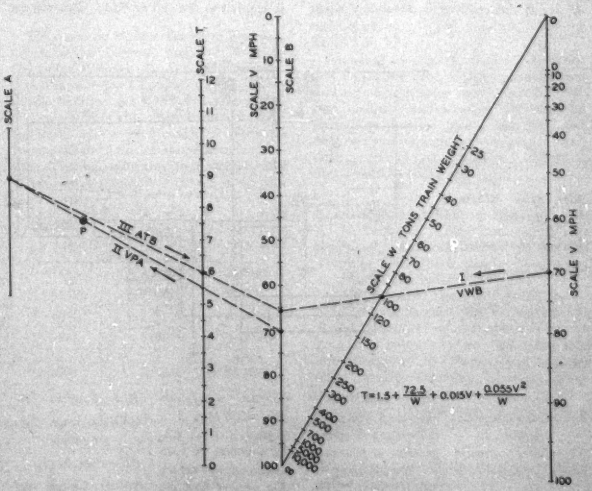
HENRY HENDRICKS KETCHAM (M'23)

Editor, International Correspondence Schools, Scranton, Pa.)

Electric Locomotive Application

To the Editor:

Herewith the writer's train resistance nomographical chart of the formula on page 1211 of AIEE *Transactions*, volume 60, 1941, in the paper entitled "Electric Locomotive Application" by E. W. Brandenstein and D. R. MacLeod (pages 1210–15). Drawn upon the chart in dashed lines is a numerical example, graphically computed: To find the train resistance T in pounds per ton for a train of 100 tons (W) at 70 miles per hour (V), draw computing secant I from 70 on



Nomographical chart of train resistance

(right-hand) scale *V*, through 100 on scale *W*, continuing it to intersect scale *B*. Draw secant II from 70 on scale *V* (middle) through common point *P*, continuing it to intersect scale *A*. From this intersection draw secant III to the intersection of I on *B*. Where secant III cuts scale *T*, at 6, is the required value of the train resistance, which satisfies the equation shown on the chart. Thus by drawing only three lines across the scales of this compact nomogram the equation is graphically evaluated. *T* increases with the speed and decreases with the weight of the train. Turning scale *B* coincides with scale *V*. Turning scales *A* and *B* are not graduated. The point *P* is an isolated point on a scale through which *all* secants II pass.

Arrows show direction in which the secants are to be drawn; Roman numerals, the order in which they are drawn; and the letters, the three scales through which each secant passes.

CARL P. NACHOD (A'07)

Vice-president, Nachod and United States Signal Company, Louisville, Ky.)

Air Raid Alarm Device

To the Editor:

Under the rules as laid down by the United States Army in Signal Circular 8-2 it is necessary that stations on certain frequencies monitor a designated key or key-relay broadcast station, in order to receive the 30-second 1,000-cycle warning tone, and abide by the instructions which follow. It was found to be necessary to assign three men to monitoring duty in order to cover the 24 hours of each day.

To eliminate this useless waste of manpower, a device was developed, by the use of which the receiver is absolutely silent until a 1,000-cycle tone is sent out for a period of ten seconds. This then turns on the speaker automatically with a terrific blast, which eliminates any possibility of failure to receive the alarm through failure of the human element, thus giving a definite audible alarm.

We used an ordinary receiver capable of high audio output and inserted a filter between the grid of the output tube and ground which attenuated all but 1,000 cycles. When the first relay *RL*1 is not energized its back contact provides power to a second high resistance relay *RL*2 which will remain energized for about ten seconds because it is crossed by a large capacitor *C*2. When an extended note of 1,000 cycles is received, the armature of the first relay *RL*1 does not return to its back contact to recharge *C*2, causing the second relay *RL*2 to trip out, which energizes a third relay *RL*3, the contacts of which connect the speaker into the circuit and remove the filter *X*1, *C*1. Thus an audible alarm is given and the receiver operates normally until the device is reset by the push button *PB*. The receiver used was a General Electric model *K*-63.

The filter *X*1–*C*1 offers a high impedance to frequencies from 900 to 1,100 cycles with its peak at 1,000 cycles. All other frequencies are bypassed to ground through contact "*A*" of *RL*3. Transformer *T*2 is connected with its low impedance toward the output transformer *T*1 of the set, its output being connected to the coil of *RL*1 through Rectox unit *RX*.

With the switch *S*1 in the alarm position, push button *PB* is closed momentarily to charge *C*2, thus closing contact "*B*" of *RL*2. This switch also closes the primary of *T*2 to ground. The output of the receiver, after attenuation of certain frequencies by *X*1–*C*1, flows through *T*2 and is applied to the coil of *RL*1. The voltage at this point normally ranges from one to three volts. During periods of about 1,000 cycles the voltage across *RL*1 rises to about five volts, opening contact "*A*" of *RL*1, thus removing the charging source of *C*2.

While *C*2 is charged, or during periods when contact "*A*" of *RL*1 is closed, the armature of *RL*2 is up, closing contact "*B*" of *RL*2 thus forming holding circuit for *RL*2. Should an extended frequency near 1,000 cycles occur (ten seconds) contact "*A*" of *RL*1 is held open and the charge in *C*2 leaks off through *R*2 and *RL*2. When the armature of *RL*2 falls back against its contact "*A*", relay *RL*3, is energized, thus opening its contact "*A*" and removing the filter *X*1–*C*1 from the circuit. At the same time, contact "*B*" of *RL*3 is closed connecting the speaker back into the circuit, giving an audible alarm.

By placing the switch *S*1 in the nonalarm position the receiver is made to operate normally, having *RL*3 energized through contact "*A*" of *RL*2, placing the speaker in the circuit, and removing filter *X*1–*C*1.

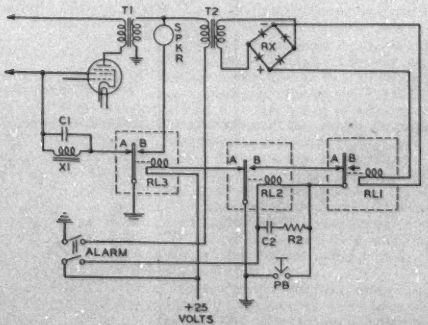
About 25 volts for operation of *RL*2 and *RL*3 is taken from the "*B*" plus of the receiver through a resistance.

Note: We would have used a lower resistance for *RL*1 if we could have purchased one.

Take steps to maintain proper bias on output tube (resistor or bias cells), otherwise the life of this tube will be much less than normal.

LIEUTENANT ARTHUR H. VICKERSON,
SERGEANT ROBERT L. GRAY

(Police Department, Boston, Mass.)



Air raid alarm device

(Patent rights reserved)

T1—Output transformer of set
T2—United Transformer Company type S14 transformer (not critical—use any plate to five-ohm voice-coil transformer)
RX—Copper-oxide rectifier
X1—United Transformer Company 39019 choke
C1—0.025 microfarad
RL1—"Sigma" 2,000-ohm relay (use any relay that will operate on three to four volts direct current)
RL2—"Sigma" 5,000-ohm relay
C2—240 microfarads
R2—5,000 ohms (Values of RL2, C2, R2 determine the time element of the device. Any relay of high resistance is suitable)
RL3—Struthers-Dunn CXB-51 relay (type not critical)
PB—Push button
S1—Double-pole toggle switch

Man-Hours or Efficiency for Increased War Effort

To the Editor:

Our greatest progress in the furtherance of our present war effort is not going to be by building more plant but by using more efficiently the plant we have. The greatest error we have made so far is that we think of production in terms of man-hours rather than in terms of what that man in that hour can do.

When we begin to increase the efficiency of our present operations it will be a very simple thing to double our present production with the same number of man-hours. We can, inside of another few months, double that again if the efficient methods which the industrial geniuses know can be applied and are enthusiastically followed.

As an example of this, in the present building of ships $^1/_4$-inch and $^9/_{32}$-inch electrodes are largely being used for welding. If these should be changed to $^5/_{16}$-inch, and $^1/_4$-inch, the speed of welding would be more than doubled. The cost of the electrode also would be reduced, the production of electrode by the same number of man-hours would be increased, and the reliability of the joint would be increased.

The great problem we have is not more welders, more shipyards, and more men

but more efficiency with what we now have. Man-hours alone will never beat the Axis, as we are seeing. The efficiency possible by the application of industrial genius will.

J. F. LINCOLN (F'39)

(President, Lincoln Electric Company, Cleveland, Ohio)

Evaluating Determinants

To the Editor:

In the 1941 AIEE *Transactions* (pages 1235–41) appeared "A Short Method for Evaluating Determinants and Solving Systems of Linear Equations With Real or Complex Coefficients," by Prescott D. Crout. Although this use is not explicitly mentioned, the procedure outlined may be used as a very systematic and general form of "network reduction." In particular, it may be used to obtain the impedance of any given network when viewed from any given pair of terminals. Investigation will show that the mathematical steps involved in setting up the "auxiliary matrix" are equivalent to automatically making various delta to wye transformations in the circuit.

Crout's method has the advantage that the entire network may be considered at once, mutual impedances between the various elements being considered at all times, and the reduction to the equivalent impedance effected through a very systematic procedure which, by carrying a check column, offers a check on accuracy after every reduction.

Suppose that the impedance of the network shown in Figure 1 as viewed from the terminals, is desired. The procedure is:

1. Draw in the necessary number of mesh currents, taking as one of the mesh currents, the current that would flow through the terminals if they were short-circuited.

2. Write the impedance matrix for the network, using as the last row and column, the mesh which includes the terminals.

3. Calculate the auxiliary matrix by the method explained by Crout. The last diagonal term thus calculated will be the impedance of the network as viewed from the terminals.

4. The "distribution factors" giving the other currents as a per unit of the terminal current are then readily obtained by calculating the final matrix.

5. A check column may be appended if it is desired to check the accuracy of every reduction in calculating the auxiliary $\mathcal{Z}$.

For the network shown in Figure 1,

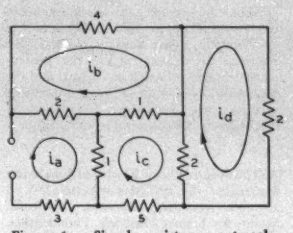


Figure 1. Simple resistance network

where, for example, Dist $(i_c) = -(1.0000) \times (-0.1250) - (0.3091)(-0.125) = 0.1636$.

The equivalent resistance of the network as viewed from the terminals is therefore 5.2182 ohms, and the distribution factors are also immediately obtained.

Further modifications of the method may be given. For instance, if the original matrix had been arranged with the c row as the last row, then the last diagonal term in the auxiliary matrix would have been the transfer impedance between the a and c meshes (or, more correctly, the reciprocal of the transfer admittance between the a and c meshes). This same quantity could, of course, be obtained from the present example simply by dividing the equivalent resistance between terminals by the distribution factor of the i_c mesh current.

W. H. HUGGINS (Enrolled Student)

(Oregon State College, Corvallis)

Criteria for Neutral Stability of Transformer Circuits

To the Editor:

The paper by Messrs. Shott and Peterson, "Criteria for Neutral Stability of Wye-Grounded-Primary Broken-Delta-Secondary Transformer Circuits" (AIEE *Transactions*, volume 60, 1941, November section, pages 997–1002), gives comprehensive treatment to a subject which for years has been difficult in theory and elusive in practice. The following may be of interest since it describes a related trouble not dealt with in the paper.

The difficulty occured on a distribution system in which grounds on 5,000-volt 60-cycle three-phase circuits are indicated by installations of potential transformers solidly tied to the busses.

It was found necessary to protect these transformers against burnouts resulting from accidental crossups with d-c circuits, specifically trolley wires (600 volts) and series arclight loops (about 6,000 volts). This was done by installing blocking capacitors between neutrals and ground. It was then found that grounds on the distribution circuits sometimes set up dangerous oscillations between capacitor and transformers. It appeared to be 60-cycle series resonance, and consideration of the transformers' saturation characteristic showed that it might occur in a range of capacitances from about 0.1 to 1.0+ microfarads.

This hypothesis was checked by experiment. Voltages of about 10,000 were observed, and currents through the potential transformer primaries were more than 100 times normal: enough to cause failure in less than half an hour. Resistance loading of the secondaries failed to remedy the situation, but insertion of 2,500-ohm resistors in series with the capacitors appears to have been completely effective. Sensitivity of ground indication is not impaired.

JEROME J. TAYLOR (A'40)

(Electrical engineer, The Detroit Edison Company, Detroit, Mich.

$\mathcal{Z} =$

	d	c	b	a	ch
d	4.0000	−2.0000	0.0000	0.0000	2.0000
c	−2.0000	9.0000	−1.0000	−1.0000	5.0000
b	0.0000	−1.0000	7.0000	−2.0000	4.0000
a	0.0000	−1.0000	−2.0000	6.0000	3.0000

Aux $(\mathcal{Z}) =$

d	4.0000	−0.5000	0.0000	0.0000	0.5000
c	−2.0000	8.0000	−0.1250	−0.1250	0.7500
b	0.0000	−1.0000	6.8750	−0.3091	0.6909
a	0.0000	−1.0000	−2.1250	5.2182	1.0000

Dist $(I) =$

d	c	b	a
0.0818	0.1636	0.3091	1.0000

NEW BOOKS • • •

Handbook of Civilian Protection. Edited by L. L. Snyder, R. B. Morris, and others. McGraw-Hill Book Company, Whittlesey House, New York, 1942. 184 pages, illustrations, etc., 7½ by 5 inches, fabrikoid, $1.25.

Intended to provide the basic information which the general public should have concerning protection in air attacks. Air-raid conduct and services, fire fighting, incendiary bombs, poison gas, first aid, civilian conservation and salvage, and wartime nutrition are discussed. There is also a bibliography.

Practical Construction of Warships. By R. N. Newton. Longmans, Green and Company, London, New York, and Toronto, 1941. 318 pages, illustrations, etc., 10 by 6½ inches, cloth, $6.

This textbook, based on courses at the Royal Naval Engineering College and the Royal Naval Dockyard, deals with the principles of construction and erection of the structure, and the more important ships' services of modern warships. Chapters on launching, docking and undocking, and on the prevention of corrosion are included.

Short Course in Tensor Analysis for Electrical Engineers. By G. Kron. John Wiley and Sons, New York; Chapman and Hall,

London, 1942. 250 pages, diagrams, etc., 9½ by 6 inches, cloth, $4.50.

Contains a series of lectures delivered to students in the advanced course in engineering of the General Electric Company. It provides a short outline of the tensorial method of attack of certain problems in electrical engineering and shows its application to those confronting the power engineer.

Illumination Engineering. By W. B. Boast. McGraw-Hill Book Company, New York and London, 1942. 274 pages, diagrams, etc., 9½ by 6 inches, cloth, $3.

The purpose of this text is to give electrical engineering students the fundamental concepts of illumination, their historical background and interrelationships. Present electrical sources of light are discussed in addition to the design and testing of illumination systems. A list of recommended standards for commercial, industrial, and public interior illumination is included.

How to Read Electrical Blueprints. By G. M. Heine and C. H. Dunlap. American Technical Society, Chicago, Ill., 1942. Illustrations, etc., 8½ by 5⅓ inches, cloth, $3.

The symbols used to represent the various pieces of electrical equipment as indicated on blueprints are discussed and separate sections deal with house wiring and automobile wiring as well as with motor and generator diagrams.

Electric Motors in Industry. By D. R. Shoults and C. J. Rife, edited by T. C. Johnson. John Wiley and Sons, New York; Chapman and Hall, London, 1942. 389 pages, illustrations, etc., 9½ by 6 inches, cloth, $4.

Written for the industrial engineer, this book presents information on the characteristics and control of electric motors which is intended to aid in the efficient selection and installation of the proper equipment. Description of the mechanical construction of motors is given to aid in understanding their operation, and a discussion of the principles and applications of electronic devices is included, but no attempt has been made to cover the generation, transmission, or distribution of power.

Electromechanical Transducers and Wave Filters. By W. P. Mason. D. Van Nostrand Company, New York, 1942. 333 pages, diagrams, etc., 9½ by 6 inches, cloth, $5.

Aims to set forth the fundamental analogies and interconnections between electrical theory and mechanical theory. Electrical network theory is analyzed and applied to lumped mechanical systems; acoustic equations and the vibration of membranes and plates are dealt with; and the form and design of electromechanical elements and systems are discussed.

Introduction to Electrochemistry. By S. Glasstone. D. Van Nostrand Company, New York, 1942. 557 pages, diagrams, etc., 9½ by 6 inches, cloth, $5.

Aims to provide an introduction to electrochemistry in its present state of development. The activity concept, the interionic attraction theory, the proton-transfer theory of acids and bases, and the consideration of electrode reactions as rate processes are discussed. A chapter on electrokinetic phenomena is also included.

ASTM Standards on Electrical Insulating Materials. By ASTM committee D-9 on electrical insulating materials. American Society for Testing Materials, Philadelphia, Pa., December 1941. 448 pages, illustrations, etc., 9 by 6 inches, paper, $2.25.

Contains specifications and test methods in their latest form as well as the current report of the committee on electrical insulating materials. The report outlines the committee's work and gives proposed revisions of standards. Several appendixes discuss the significance of various tests.

The "Particles" of Modern Physics. By J. D. Stranathan. Blakiston Company, Philadelphia, Pa., 1942. 571 pages, illustrations, etc., 9½ by 6 inches, fabrikoid, $4.

Presents the material considered essential to an appreciation of modern physics and the newer concepts of atomic structure. The experimental evidence upon which each concept is founded is stressed throughout. The book is intended both as a fundamental text in its field and as a reference work for advanced students. A number of specific references have been included as footnotes.

Procedure Handbook of Arc Welding Design and Practice. 7th Edition. The Lincoln Electric Company, Cleveland, Ohio, 1942. 1,308 pages, 6 by 9 inches, illustrations, etc., simulated leather, $1.50.

An explanation of the methods and techniques used in welding, this manual aims to present the most recent information on welding symbols, new allowable stresses, pre-heating for welding, stress relieving, speeds and costs, tubular construction, weldability of aluminum alloys, general metallurgical characteristics of metals and alloys, and appearance and styling of welded design. Typical applications of arc welding are given detailed emphasis.

Welding Handbook. Edited by W. Spraragen. American Welding Society, New York, 1942. 1,593 pages, illustrations, cloth, $6.

Intended to present up-to-date information on welding for use as a textbook and reference manual in engineering and trade schools. The book aims at covering the physics and metallurgy of welding and the weldability of steels; welding and allied processes; materials used; training, inspection, and safety; design considerations and testing of welding; and the applications of welding.

Training Manual for Auxiliary Firemen. Edited by Horatio Bond, W. Fred Heisler, R. J. Douglas. National Fire Protection Association, Boston, Mass., 1942. 416 pages, diagrams, etc., 7⅜ by 5¼ inches, paper, $1.50.

A textbook intended for the instruction of newly recruited auxiliary firemen. It covers courses on civilian defense, control of incendiaries, gas masks for war gases, and primary and secondary courses in fire fighting and control. Supplementary material is included for advanced training.

Handbook of Mechanical Design. By G. F. Nordenholt, J. Kerr, and J. Sasso. McGraw-Hill Book Company, New York and London, 1942. 277 pages, diagrams, etc., 11 by 8½ inches, cloth, $4.

Presents practical methods and procedures which have been in use in engineering designing departments. Chapters cover charts and tables for general arithmetical calculations; the properties of materials; beams and structures; latches, locks, and fastenings; springs; power transmission elements and mechanisms; drives and controls; and design data on production methods. The information is chiefly presented as charts, nomograms and tables, and in drawings.

PAMPHLETS . . .

The following recently issued pamphlets may be of interest to readers of "Electrical Engineering." All inquiries should be addressed to the issuers.

Definitions of Welding Terms and Master Chart of Welding Processes. American Welding Society, New York, 1942. 31 pages, 40 cents.

Standard Methods for Mechanical Testing of Welds. American Welding Society, New York, 1942. 25 pages, 40 cents.

National Emergency Steels. American Society for Metals, Cleveland, Ohio, 1942. 35 pages, 25 cents.

Depreciation of Group Properties (Bulletin 155). By Robley Winfrey. Iowa State College, Ames, Iowa, 1942. 131 pages, no charge.

Plastics From Agricultural Materials (Bulletin 154). By O. R. Sweeney and L. K. Arnold. Iowa State College, Ames, Iowa, 1942. 52 pages, no charge.

Standards on Radio Wave Propagation: Measuring Methods (supplement to the *Proceedings* of the Institute of Radio Engineers, volume 30, No. 7, Part II). IRE, New York, 1942. 16 pages, 50 cents.

Standards on Radio Wave Propagation: Definition of Terms (supplement to the *Proceedings* of the Institute of Radio Engineers, volume 30, No. 7, Part III). IRE, New York, 1942. 8 pages, 20 cents.

Standards on Facsimile (supplement to the *Proceedings* of the Institute of Radio Engineers, volume 30, No. 7, Part IV). IRE, New York, 1942. 5 pages, 20 cents.

TRANSACTIONS SECTION

Preprint of Corresponding Pages From the Current Annual AIEE Transactions Volume

Any discussion of these papers will appear in the December 1942 Supplement to Electrical Engineering—Transactions Section

Frequency Control of Load Swings

J. E. McCORMACK
MEMBER AIEE

R. J. LOMBARD
NONMEMBER AIEE

Synopsis: The Consolidated Edison Company made a series of tests to determine the cause and extent of system load swings on generators and tie feeders. The results were reported in detail in a previous paper.[1] An analysis of these tests indicated ways in which our load dispatching methods could be improved. This paper reports the effect of the changes in the method. Our experience indicates that the operators may reduce tie and generator load swings to negligible values by using frequency to control manual adjustments of generator output, provided that an accurate frequency indication is available at each generating station.

SEVERAL of the principles reported in the previous paper[1] have been applied to our method of load dispatching to reduce the load swings on the tie feeders and generators. These principles are:

1. Major load swings are caused by manual operation of governor valves in one or more stations during periods of load change.

2. Governors or supplementary controllers do not contribute to load swings but operate continuously to check them.

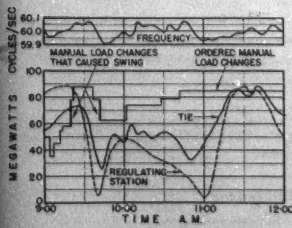


Figure 1. Load swing caused by load changes ordered by the system operator

The load changes were made when they drove the frequency away from normal

3. A change in voltage will result in a change in both real and reactive load demand, but a change in frequency within reasonable limits and with constant voltage does not result in an appreciable change in system demand.

4. The instantaneous relations between load, voltage, and frequency serve to indicate the initiating cause of a load change. An initial change in any one of these quantities will affect the other as shown in Table I.

Table I

Initiating Change	Effect on Voltage	Effect on Load	Effect on Frequency
Voltage			
Increase	—	Increase	Decrease
Decrease	—	Decrease	Increase
Load			
Increase	Decrease	—	Decrease
Decrease	Increase	—	Increase
Frequency			
Increase	Increase	Increase	—
Decrease	Decrease	Decrease	—

Effect of Manual Adjustments of Generator Output

On a system supplied from one turbo-generator, a manual adjustment of the steam input would be readily discernible in the speed and voltage. This effect is not so apparent on a large system, because there are many governors and controllers operating to compensate the change. A change in steam input in excess of the load requirement on the one unit system results in a relatively large speed change, while on the large system, it results in a load swing over the connections between generators. On a large system the generator on which a manual load adjustment is made will have a simultaneous change of speed and load in the same direction, while all other units, under the influence of their respective governors, will change load in a direction opposite to the frequency.

If the generator ouput at one station is increased by manual adjustment when the frequency is at or above normal, the governors at the other stations will reduce the generated load by an equal amount. If these other stations are operating on scheduled loads the station operators will make manual adjustments to restore their stations to schedule, thus driving frequency still higher. This jockeying of load between stations results in load swings on the tie feeders, as well as on the stations, and imposes an unnecessary burden on a station assigned to regulation of frequency.

An example of load swing caused by manual adjustments without regard to instantaneous frequency is shown in Figure 1. This type of load swing can be avoided if the system frequency is used as a control in making manual adjustments.

Load-Dispatching Methods

It was the practice of the system operator to assign blocks of load to each station from time to time on the basis of an advanced estimate of the load requirements. Past experience with the hour-to-hour changes in total system demand was used in making the estimate. The station operators made the load changes when ordered, regardless of the frequency at that time. If the system demand did not change exactly as anticipated, the ordered changes would cause the frequency to depart from normal, and a

Paper 42-113, recommended by the AIEE committee on power generation for presentation at the AIEE summer convention, Chicago, Ill., June 22-26, 1942. Manuscript submitted April 7, 1942; made available for printing May 19, 1942.

J. E. McCORMACK and R. J. LOMBARD are both with Consolidated Edison Company of New York, Inc., where Mr. McCormack is assistant outside plant engineer.

system-wide load swing would result as the governors and controllers operated to compensate for the excess change. Where the tie feeders are relatively small in capacity, or where for contractual reasons the tie feeder interchange is to be maintained at a fixed value, it is then necessary to make additional adjustments to restore the tie-feeder load to normal.

In order to minimize these load swings, the following changes were made in our load-dispatching methods. The system operator now estimates the load in advance but assigns load to each station in larger blocks and at less frequent intervals. When the station operator receives a load-change order, he executes the order only at an instant when the change will tend to restore the frequency to normal. In other words, the station operator increases load only with low or dropping frequency and decreases load only with high or rising frequency. Thus, errors in load anticipation which could cause load swings are automatically eliminated.

The system operator has authority to make load changes, regardless of frequency, should changes be necessary, but he must specifically state that this shall be done.

We would like to point out that these measures are not intended to maintain closer frequency or to keep the accumulated time error within narrow limits, but are for the purpose of reducing, by the use of indicated frequency, the unnecessary load swings on generating facilities and tie feeders.

Figure 2 shows the extent that load swings have been reduced by the present method of load dispatching.

Need for Accurate Frequency Indication

Frequency indication as a control in making manual load adjustments requires that each station have a suitable frequency indicator. Since the normal frequency band on the system is about 0.1 cycle per second, an instrument for this purpose would have to be accurate within a fractional part of this normal band. This accuracy should be in the neighborhood of one part in 50,000, which is beyond the capability of the conventional frequency meter. A meter of normal accuracy could be used if one meter sent impulses to all stations indicating whether the frequency was high or low. Another way would be by transmitting a standard frequency voltage and comparing it differentially with another voltage at system frequency at each station.

On our system a standard frequency accurate to better than one part in a million is available.[1] This standard frequency is transmitted to each major station and compared with the system frequency by means of a synchroscope. The synchroscope gives one revolution for each cycle of slip frequency between the standard and system frequencies. The direction of rotation indicates whether the system frequency is high or low, and the rate of rotation is a measure of the amount of departures from standard frequency. Each station operator therefore has the same indication of system frequency.

This method of transmitting a frequency standard has been practical on the Consolidated Edison Company system because of the relatively few large stations and the short distances between them. In order to use a similar scheme over a widespread system, we have developed a frequency indicator operating from a frequency standard received by radio. Figure 3 shows the schematic diagram of this device. This scheme is based upon sending a standard frequency by a radio transmitter which has sufficient signal strength to cover the area of the system.

The radio signal is amplified by a radio receiver at each station, and the amplified standard-frequency voltage output is impressed on a step-up transformer. The transformer supplies a neon tube which is circular in shape and is covered by a disc having a single slot. The disc is driven by a synchronous motor from the power system. The standard frequency in cycles per second must be exactly divisible by the motor synchronous speed in revolutions per second. When the device is in operation, and the neon tube is viewed through the slotted disc, a series of light spots evenly spaced in a circle will be seen. If these spots remain stationary, the system frequency at that time is correct. If the spots rotate, the system frequency is incorrect. The direction of rotation indicates whether the system frequency is above or below the standard frequency.

A few trial installations of this device are in service using an existing standard-frequency broadcast by the Bureau of Standards in Washington. This signal is broadcast on a carrier frequency of five megacycles and modulated by a 440-cycle tone. A 1,200-rpm synchronous motor is used to drive the slotted disc. The experience with this device has been very satisfactory.

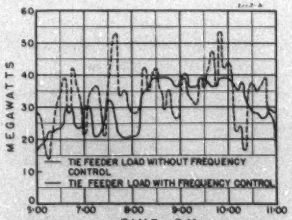


Figure 2. Effect of frequency control of manual load changes on tie-feeder loads

When load changes are made independent of system frequency, the tie-line loads vary considerably. When the load changes are made so that they restore frequency to normal, the large rapid load changes are not experienced

Conclusion

The results of a year's experience using frequency as a control in making manual load changes on the Consolidated Edison Company system have led us to the following conclusions:

1. Generating-station and tie-feeder load swings can be reduced to a point where load swings are no longer a problem.
2. The need for accurate load anticipation becomes less important.
3. Tie feeders can be loaded safely to their thermal or stability limits.
4. Interchange energy between parts of the system may be controlled within closer limits. For contractual reasons this is often important.
5. Boiler-room maintenance costs can be decreased by reducing the load swings on the boilers.
6. Manual load adjustments by the station operator can be normally made in a direction to aid the automatic governors or controllers.

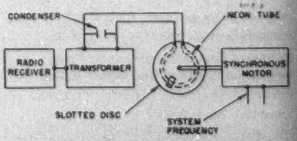


Figure 3. Schematic diagram of stroboscopic method of frequency indication based upon a standard frequency received by radio

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The Effect of Initial Conditions on Subharmonic Currents in a Nonlinear Series Circuit

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Synopsis: This paper shows the importance of switching time as an initial condition for the current in a simple nonlinear series circuit with a saturable inductor. It is also shown that initial flux linkages in the inductor have an important effect on the current response during the first few cycles after closing the switch. It is emphasized that all experimental work was done with voltages below the critical ferroresonant voltage.

IT is the purpose of this paper to report the results of a study of the effect of switching time on the current response in a series R, L, C circuit containing a saturable inductor. In previous experimental work no attempt has been made to control the initial angle of the sinusoidal applied voltage.

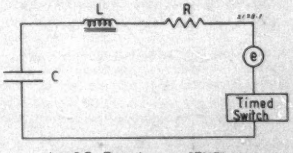
This series nonlinear circuit has been the subject of considerable investigation. Its importance was recognized in this country when outages caused by abnormally high currents were experienced in transmission lines equipped with series capacitors. It was found that the observed abnormal currents had a frequency lower than the system frequency. The frequency was a submultiple of the fundamental; hence, they were called "subharmonic" currents. Concordia[1] and Butler solved the equations of the circuit for the parameters of interest in their transmission-line problem by employing a differential analyzer. Following this work Travis[2] and Weygandt approached the problem analytically with the method of matching boundary conditions. They were forced to make many simplifying assumptions, but the solutions they obtained give an insight into the mechanism of the production of subharmonic currents in this circuit. One of the most serious assumptions, namely, that of neglecting capacitance in the circuit when the inductor is saturated, was removed by I. Travis[3] in a later paper. The theoretical investigation has reached a point where a great amount of computation must be done to obtain a small amount of information. To study the performance of this circuit further J. D. McCrumm[4] has employed an experimental method which consists of a systematic variation of circuit parameters, and recording of wave forms on oscillograms. The currents in his circuit were initiated by the random closing of a knife switch.

Experimental Procedure

The circuit studied is shown in Figure 1. The timed switch is constructed so that it can be closed at any point of the 60-cycle sine wave. After closure, it remains closed for the duration of four cycles, and then opens. Two cycles later it closes again at the same switching angle as before. This repetitive closing and opening enables the experimenter to view the first four cycles of the current as a steady image on an oscilloscope screen. During the two cycles that no voltage is applied, the capacitors are short-circuited to insure that the initial charge is zero. With this timed switch it is possible to watch the change of wave form as the switching angle is varied and also while various circuit parameters are varied. Provision was made to keep the switch closed after one of its periodic closures. This enables the experimenter to make oscillograms of the current from the time of initiation. Details of the timed switch are given in the appendix.

Results

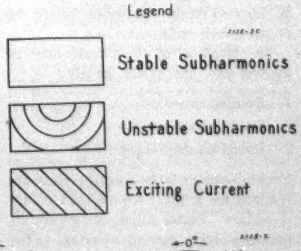
The effect of initial voltage phase angle on the circuit response is best shown by

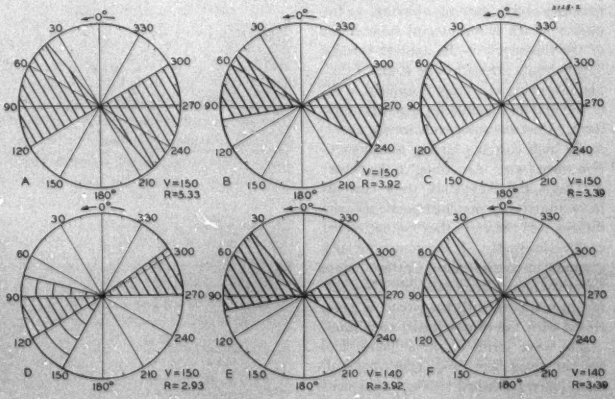


L = G.E. Transformer 9TM754A1
C = 355 Mfds. (Leakage 2000 Ohms)
R = Varied
$e = 12 E \sin(\omega t + \Phi)$

Figure 1. Circuit diagram

Figure 2. Polar diagrams showing the type of circuit response for the full range of initial voltage phase angle





Paper 42-128, recommended by the AIEE committee on basic sciences for presentation at the AIEE summer convention, Chicago, Ill., June 22-26, 1942. Manuscript submitted February 26, 1942; made available for printing May 19, 1942.

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The author wishes to express appreciation to his adviser, C. N. Weygandt, for help, and to the General Electric Company for plans of the relay employed in the experiment. This work was done at the Moore School of electrical engineering, University of Pennsylvania, Philadelphia, Pa., during the term 1939-40. Financial assistance was given by a Moore School fellowship.

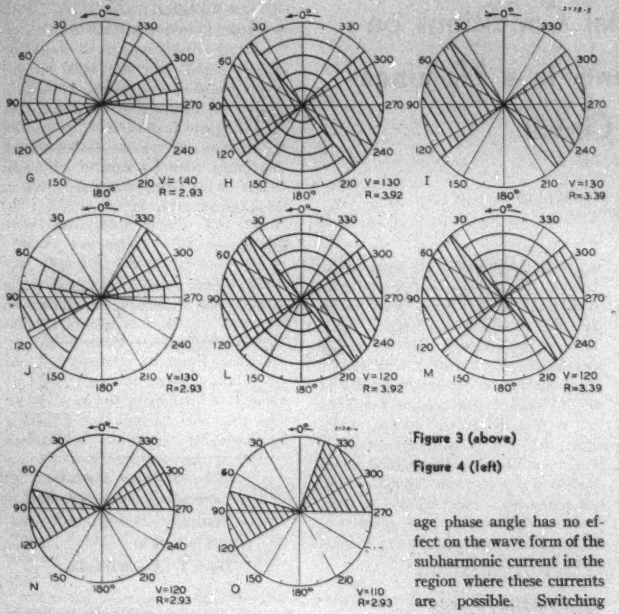


Figure 3 (above)

Figure 4 (left)

the polar diagrams of Figures 2, 3, and 4. The zero of angle was arbitrarily chosen as the zero on an oscillogram before the negative half-cycle.

The response of the circuit may be divided into three types, namely:

1. Exciting current.
2. Stable subharmonics.
3. Unstable subharmonics.

Exciting current is the normal current in a transformer primary for no load on the secondary. Stable subharmonics are abnormally high currents having a frequency which is an integral submultiple of the frequency of the applied voltage. The currents are said to be stable if they persist as long as voltage is applied to the circuit and they maintain a repetitive wave form. Unstable subharmonics are abnormally high currents having a nonrepetitive wave form. According to the theory of Travis and Weygandt, these currents have imperfectly matched boundary conditions, and therefore they cannot repeat each cycle exactly. It is common for such currents to continue in a "jittery" state for many minutes and suddenly disappear not to reappear until the circuit is again closed with the proper initial conditions.

The wave forms of the subharmonics are not given here, since many have already been published.[4] The initial voltage phase angle has no effect on the wave form of the subharmonic current in the region where these currents are possible. Switching angles of 90 degrees and 270 degrees generally give an exciting-current response, and the unstable subharmonics are situated on the border line between exciting current and stable subharmonics.

The diagrams of Figures 2, 3, and 4 show also that the subharmonic region is smaller for high values of circuit resistance. In the circuit of Figure 1, subharmonics could not be initiated at any angle when the resistance R was greater than approximately seven ohms. The extent of the subharmonic region also decreases as the applied voltage decreases. This is to be expected, because the lower the voltage, the more difficult it is to saturate the core of the inductor.

The boundary lines between current regions are drawn sharply but actually it is difficult to tell within plus or minus five degrees where one region ends and another begins. These graphs then have only a semiquantitative value. Each diagram is the result of observations taken at least two complete cycles of 360 degrees to be certain that the results are reproducible.

Another possible initial condition which has not been previously investigated either theoretically or experimentally is the initial flux in the inductor core. Oscillograms were taken with the transformer winding flashed with d-c before the switch was closed. Figure 5 shows two oscillograms taken of current initiated with identical initial conditions, except that the inductor was flashed in one direction for one oscillogram, and in the reverse direction for the other. It can be seen that the first few cycles are very different, but the wave forms after a short time has elapsed are identical. Figure 6 shows a repetition of the experiment for a different set of initial conditions.

Conclusions

The results of this study may be summarized as follows:

(*a*). The current response in this circuit is dependent on the initial voltage phase angle.

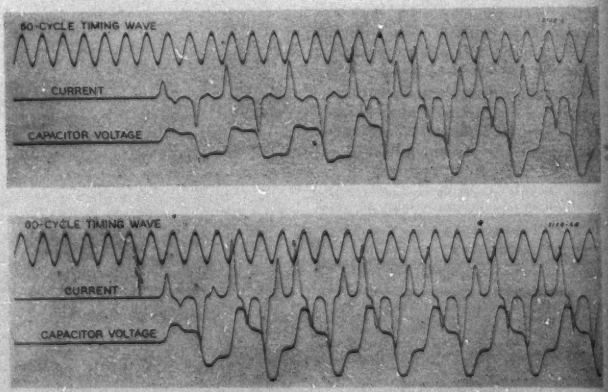
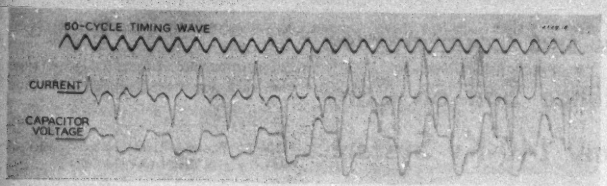


Figure 5. Oscillograms showing the current response of the circuit for identical initial conditions except that the initial flux in the inductor core was reversed

The initial voltage angle was 31 degrees. Other data are $R = 2.93$ ohms, $V = 120$ volts, and $q_0 =$ zero



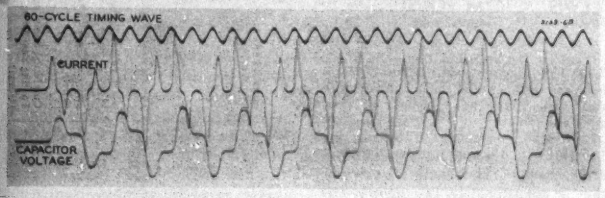


Figure 6. Oscillograms made in a manner similar to those of Figure 5

In this case the initial phase angle was 266 degrees. Other data are $R = 2.93$ ohms, $V = 140$ volts, and $q_0 =$ zero

(*b*). The wave form of stable subharmonics is independent of initial phase angle.

(*c*). The wave form of the first few cycles of a subharmonic current is dependent on the value of initial flux linkages in the inductor.

Figure 7. Schematic diagram of the relay and associated circuits

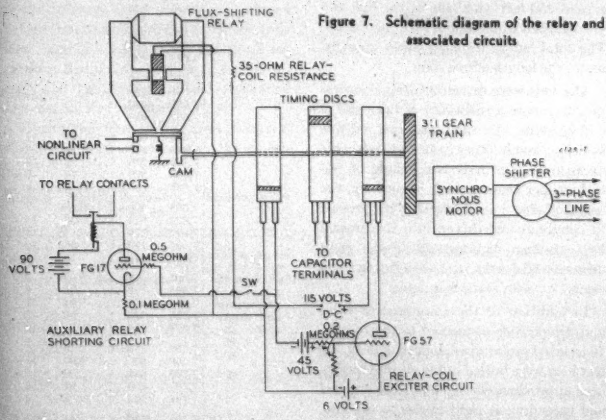
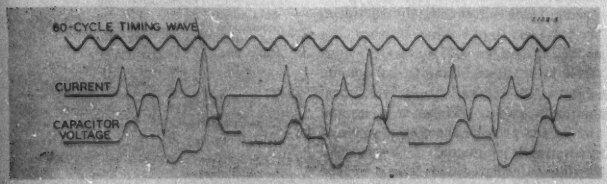


Figure 8. An oscillogram illustrating the performance of the timed switch

Note that the wave forms are repeated in detail. Note also that the capacitor voltage is reduced to zero after the switch opens so that $q_0 =$ zero for the next closure

It should be noted that nothing has yet been said about ferroresonance. The impressed voltages employed in this work were lower than the critical voltage for ferroresonance in all cases. All statements concerning initial conditions, therefore, apply only to subharmonic currents. It is certain that the currents of ferroresonance are abnormally high, but the frequency is that of the applied voltage. This point is stressed, because some confusion is apparent in the discussions of other papers.



Appendix

The timed switch discussed under experimental procedure was a mechanical flux-shifting relay. A mechanical relay was employed, because it is necessary to have the circuit resistance very low. This eliminates the possibility of using electronic switches, because they have a high internal resistance, and furthermore this resistance is a function of the current.

Figure 7 shows a schematic diagram of the relay and the associated circuits. The purpose of the circuits is to excite the flux-shifting coil on the relay at the proper time. The timing is effected as follows:

(*a*). A synchronous motor running at 1,800 rpm turns three coaxial disks at 600 rpm through a 3 to 1 gear train.

(*b*). One disk has a shorting bar on the periphery which closes the bias circuit of the *FG* 17 thyratron. The thyratron plate current excites the flux-shifting coil on the relay, causing it to close. This coil excitation occurs once every six cycles. The part of the 60-cycle wave at which it occurs is determined by the space angle of the synchronous motor rotor. This space angle can be varied through 360 degrees by means of the phase shifter on the input.

(*c*). A cam is set on the end of the synchronous motor shaft so that it opens the relay about four cycles ($^1/_{15}$ second) after the closing instant.

(*d*). Another disk on the motor shaft is arranged to break the thyratron plate circuit after the arc in the tube has been initiated. This is necessary to make the tube ready for the next closure.

(*e*). A third disk on the motor shaft has a shorting bar on the periphery. This is oriented so that during the two cycles after the cam opens the relay, the charge on the capacitors in the circuit may be reduced to zero.

The oscillogram, Figure 8, shows the performance of the timed switch. Note that each cycle of operation is repeated in every detail. The result is a steady image of the first four cycles of current in the circuit on an oscilloscope screen.

The *FG* 17 circuit is switched in if it is desired to keep the circuit closed after a given closure. This circuit is used in conjunction with an oscillograph to get photographs of the current, and capacitor voltage wave forms from the time of closure until the steady state is reached.

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Study of Driven Rods and Counterpoise Wires in High-Resistance Soil on Consumers Power Company 140-Kv System

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W. W. LEWIS, FELLOW AIEE
C. M. FOUST, MEMBER AIEE

THE Consumers Power Company operates an extensive 140-kv system in eastern, southern, and western Michigan. In parts the top soil is sand, sometimes extending to a considerable depth, and tower footings in this soil have very high resistance compared with resistance encountered in other soils.

In 1936 the Consumers Power Company and the General Electric Company began a joint investigation of the ground-circuit arrangement best suited to carry the lightning current with a minimum potential across the line insulators. The test setup was arranged to study the relative merits of the driven rod, the continuous-parallel counterpoise, and the radial counterpoise, as well as to investigate the current and voltage conditions near the surface of the earth in the vicinity of the lightning stroke.

Methods of Grounding

To study various methods of grounding, a portion of the *N*-14 line between Croton and Muskegon was divided into three sections, and each section was equipped with special earth connections as follows:

Section *A*. Towers 7,659 to 7,682, parallel continuous counterpoise and right-angle counterpoise.

Section *B*. Towers 7,683 to 7,708, parallel continuous counterpoise and driven rods.

Section *C*. Towers 7,711 to 7,723, right-angle counterpoise and driven rods. (Tower 7,709 has been removed. Tower 7,710 is equipped with ground rods, but not with right-angle counterpoise because of deep gully and road.)

Figures 1a, 1b, and 1c show the three arrangements. The length of each section is approximately two miles. The counterpoise wire consists of seven-strand $\frac{3}{8}$-inch galvanized-steel cable buried to a depth of approximately 18 inches. The parallel wire extends continuously between towers, passing directly beneath the towers and connecting to the middle leg. The right-angle counterpoise wires extend 250 feet each side of the line and are attached to the side legs of the towers. The total length for each tower approximates the length of one span.

The rods were driven as deep as necessary to secure a resistance of between 10 and 20 ohms. In some cases one rod was sufficient and in other cases two rods were necessary. The rods were made of $\frac{5}{8}$-inch copper bearing steel, 8 feet long, the lengths being joined together by pressed fit couplings and driven into the ground by gasoline hammers.[1,2] Rods were driven to all depths, up to 150 feet in some cases.

In addition to the counterpoise wires and driven rods connected to the towers, 10 isolated probe wires approximately 100 feet long were buried in the ground, beginning approximately 300 feet from the line and extending at right angles to the line. These were spaced approximately uniformly throughout the experimental region between towers 7,659 and 7,723.

The *N*-14 line for the greater part of its length is a single-circuit line on steel towers. The conductors are arranged in a triangle, two on one side of the tower and one on the other, the equivalent delta spacing being approximately 15.6 feet. The total length of the line between Croton and Muskegon is 37.4 miles, of which 35.4 miles is 3/0 steel-reinforced aluminum cable and two miles 4/0 steel-reinforced aluminum cable. There is a ground wire at the peak of the towers made of three strands of number 7 Copperweld. The line is insulated with 9 disks spaced $5\frac{3}{4}$ inches on suspension and 11 disks on dead ends.

The towers are of the three-legged type and each leg was equipped with one

Table I. Footing Resistance of Towers of the *N*-14 Line

Section and Arrangement	Tower No.	Footing Resistance (Ohms)	No. of Driven Rods	Depth of Driven Rods (Feet)	Combined Resistance, Footing and Rods (Ohms)
Section *A*, parallel and right-angle counterpoise	7,659	460			
	7,660	510			
	7,661	660			
	7,662	750			
	7,663	680			
	7,664	750			
	7,665	640			
	7,666	600			
	7,667	840			
	7,668	360			
	7,669	420			
	7,670	700			
	7,671	730			
	7,672	820			
	7,673	740			
	7,674	750			
	7,675	360			
	7,676	920			
	7,677	860			
	7,678	760			
	7,679	740			
	7,680	920			
	7,681	620			
	7,682	610			
Section *B*, parallel counterpoise and driven rods	7,683	620	1	100	14
	7,684	840	1	82	15
	7,685	970	1	92	14
	7,686	520	1	76	9.5
	7,687	720	2	48-52	24
	7,688	590	2	32-36	19
	7,689	810	1	53	15
	7,690	770	2	42-41	14
	7,691	490	1	56	14
	7,692	440	1	58	10.5
	7,693	800	1	100	8.5
	7,694	675	1	100	8.5
	7,695	910	1	124	11
	7,696	775	1	90	13
	7,697	700	1	94	16
	7,698	775	1	116	11
	7,699	630	1	100	10.5
	7,700	640	1	108	10
	7,701	690	1	92	14
	7,702	680	2	58-57	14
	7,703	650	1	84	11.5
	7,704	640	1	84	10
	7,705	540	2	65-53	23
	7,706	825	1	108	10
	7,707	560	2	71-92	9
	7,708	1,400	1	92	11
Section *C*, right-angle counterpoise and driven rods	7,710*	850	2	121-92	13
	7,711	665	2	108-104	12
	7,712	910	2	98-108	13
	7,713	800	1	81	12.5
	7,714	1,030	1	100	8.5
	7,715	1,050	1	128	11
	7,716	850	1	132	14
	7,717	650	1	134	14
	7,718	810	1	156	12
	7,719	880	1	100	8
	7,720	610	2	84-100	7
	7,721	890	1	124	10
	7,722	700	1	116	7
	7,723	493	1	140	12

There is no tower 7,709.

* Tower 7,710 has two driven rods, but no counterpoise connected to it.

Paper 42-107, recommended by the AIEE committee on power transmission and distribution for presentation at the AIEE summer convention, Chicago, Ill., June 22-26, 1942. Manuscript submitted April 7, 1942; made available for printing April 24, 1942.

J. G. HEMSTREET, is superintendent of operation, Consumer's Power Company, Jackson, Mich.; W. W. LEWIS is with the central-station engineering department, and C. M. FOUST with the general engineering laboratory, both of the General Electric Company, Schenectady, N. Y.

The authors acknowledge the assistance of many people in this investigation, especially J. R. Eaton, now of Purdue University, who had active charge for Consumers Power Company of the installation of the driven rods, counterpoise wires, and measuring equipment; Carl C. Tanner, who carried on the field work after Mr. Eaton left the company; and R. F. McAtee of the general engineering laboratory, General Electric Company, who helped in the calibration work and in analyzing the data.

bracket for magnetic links. After the 1937 season, brackets were installed on the overhead ground wire on each side of every tower, about 3 feet away from the tower. The continuous counterpoise wires were equipped with brackets on each side of each tower, about 4 feet from the center tower leg, and also at the middle of each span. The right-angle counterpoise wires on each side of the tower were equipped with one bracket at 4 feet from the tower leg, and on only the south side one at 125 feet and one at 225 feet. Each separate probe wire had a bracket at approximately the middle of its length. Each driven rod was equipped with one bracket. In all cases each bracket was equipped with two magnetic links in order to obtain a current range and to make use of the oscillatory calibration.[3]

The entire test portion of the *N*-14 line extends over a very uniform flat sandy plain. Table I gives the resistance measured by ground megger of the footing of each tower of the *N*-14 line included in this investigation. These resistances are of the footings alone and were measured before counterpoise wires and driven rods were installed. The table also gives for sections *B* and *C* the lengths of the driven rods and the final combined resistance of tower footing and driven rods.

During the years 1937 to 1941 inclusive, six strokes were experienced on the experimental part of the *N*-14 line. Of these one was in section *A*, two in section *B*, and three in section *C*. Following is a brief analysis of the important features of these strokes:

Table II. Footing Resistance of Towers on the *T*-20 Line

Tower No.	No. of Driven Rods	Combined Resistance Footing and Rods (Ohms)
4,387	4	125
4,388	4	21
4,389	4	28.5
4,390	2	25
4,391	2	29
4,392	2	22
4,393	2	33
4,394	2	35
4,395	1	51
4,396	1	56
4,397		760
4,398		897
4,399		729
4,400		1,299
4,401		942
4,402		1,240
4,403		1,260
4,404		816
4,405		1,187
4,406		784
4,407		266
4,408		75
4,409		138
4,410		15
4,411		14
4,412		13
4,413		158
4,414		434
4,415		131
4,416		44
4,417		—

STROKE 1

On October 19, 1937, there was a stroke to the overhead ground wire of the *N*-14 line, between towers 7,764 and 7,765, in section *A*, equipped with parallel counterpoise and right-angle counterpoise. Current records were obtained at 14 towers, 7,659 to 7,672 inclusive. The stroke was negative, that is, all tower currents flowed upward and all parallel counterpoise currents toward tower 7,665 and all right-angle counterpoise currents toward the towers. An idea of the comparative

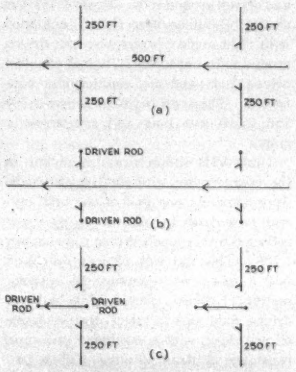

Figure 1. Experimental installation of parallel continuous counterpoise, right-angle counterpoise, and driven rods

ability of the two types of counterpoise to pick up current may be gained from the following:

For the parallel counterpoise, the difference between the current in a span approaching the tower and the current in the same span leaving the preceding tower is taken as the current collection or pickup in that span. For the right-angle counterpoise, the currents approaching the tower at each side at the magnet station nearest the tower are added up to give the pickup for that tower. Table III shows the parallel counterpoise pickup and Table IV the right-angle counterpoise pickup for this stroke. It will be noted that these currents are nearly equal, 23,000 amperes total in the parallel counterpoise and 25,700 amperes in the right-angle counterpoise.

At the first tower at which readings were obtained, tower 7,659, there were 2,800 amperes in the parallel counterpoise at the stroke side of the tower and no current was read in the counterpoise on the other side of the tower, in the tower legs, or in the right-angle counterpoise. Likewise, at the extreme end, tower 7,672, there were 1,800 amperes in the parallel counterpoise on the stroke side and no current was read elsewhere. The origin of this current is unknown.

It is interesting to note that current flowed in the parallel counterpoise for about six spans on each side of the point of stroke, while the right-angle counterpoise carried readable current at only three towers adjacent to the stroke, and the tower members themselves showed current in only two towers. This wide extent of current pickup on the parallel continuous counterpoise is common on this line, and also has been observed on other lines.[4,5]

Isolated probe conductors were installed in the ground opposite towers 7,660 and 7,667, but no current was measured in these wires. However, neither was any current measured in the right-angle counterpoise wires extending out toward the probe conductors at these towers.

It is interesting to obtain an idea of the comparative ability for collecting current of the shallow buried counterpoise wires

Table III. Parallel-Counterpoise Current Pickup, Stroke 1

Toward Croton		Toward Muskegon	
Tower No.	Amperes	Tower No.	Amperes
Beyond 7,659..	0	Beyond 7,672..	0
7,659 to 7,660..	700	7,672 to 7,671..	200
7,660 to 7,661..	500	6,671 to 7,670..	500
7,661 to 7,662..	1,000	7,670 to 7,669..	600
7,662 to 7,663..	2,200	7,669 to 7,668..	500
7,663 to 7,664..	3,100	7,668 to 7,667..	2,100
7,664 to 7,665..	4,300	7,667 to 7,666..	2,300
		7,666 to 7,665..	5,000
	11,800		11,200
			11,800
Total counterpoise pickup			23,000

Table IV. Right-Angle Counterpoise Current, Stroke 1

Tower No.	Direction of Counterpoise Wire	Amperes
7,664	North	2,500
	South	2,500
7,665	North	8,000
	South	8,300
7,666	North	2,200
	South	2,200
Total		25,700

and the short tower footings, extending perhaps eight feet below the ground surface. This may be done as follows:

Table V shows the total current picked up by the ground system, exclusive of the tower footings, which could not be measured in these tests.

Current was measured in only two towers, 7,664 and 7,665, as shown in Table VI. The difference between the total tower current of 58,400 amperes and the total counterpoise pickup current 53,300 amperes is 5,100 amperes, which is assumed to be the tower-footing pickup current.

If the current of 2,800 amperes in counterpoise at tower 7,659 and 1,800 amperes in counterpoise at tower 7,672 is prorated to the parallel and right-angle counterpoise in the ratio 23,000 to 25,700, we can sum up the distribution of currents between counterpoise and tower footings and evaluate the counterpoise resistance.

Table V. Measured Current Picked up by Counterpoise System, Stroke 1

	Amperes
Parallel counterpoise	23,000
Right-angle counterpoise	25,700
Current in counterpoise at tower 7,659	2,800
Current in counter poise at tower 7,672	1,800
Total	53,300

The multiple resistance of the 14 towers, 7,659 to 7,672, from Table I, is 42.7 ohms. The counterpoise resistance is then assumed to be inversely proportional to the current pickup, as shown in Table VII.

This comparison indicates that the counterpoise wires are very efficient compared with the natural tower footings which penetrate only a short distance below the ground in the same top soil occupied by the counterpoise wires.

Stroke 2

On August 20, 1938, there was a stroke to the overhead ground wire on the *N*-14 line between towers 7,708 and 7,710. Tower 7,709 had been removed prior to this time, so that towers 7,708 and 7,710 were adjacent. The stroke was negative, that is, cloud negative and earth positive, all tower currents flowing upward and all counterpoise currents flowing inward toward the point of stroke.

Tower 7,708 was at one end of section *B*, equipped with parallel counterpoise and driven ground rods. Tower 7,711 was at the beginning of section *C*, equipped with right-angle counterpoise and driven ground rods, but tower 7,710 had only two driven rods and no counterpoise connected. The span between towers 7,708 and 7,710 was long and ran across a gully.

Table VIII summarizes the pickup in the counterpoise wires and driven rods. Approximately one half of the total current picked up by the driven rods was collected by the single driven rod at tower 7,708. This rod was 92 feet deep and had a measured resistance of approximately 11 ohms. Tower 7,710 had two driven rods, one 121 feet deep and one 92 feet deep, with a combined measured resistance of about 13 ohms. These two rods, however, picked up only 4,200 amperes total. It appears that ground currents flowing in the gully at right angles to the line were tapped more readily by the single rod at tower 7,708, possibly because of soil resistance in the vicinity and also possibly because the cloud may have been centered more to the north of the gully (toward tower 7,705).

The set of readings in the parallel-counterpoise and driven-rod section, towers 7,705 to 7,708 inclusive, lends itself to a determination of the equivalent resistance of the counterpoise, on the assumption that the resistances are inversely as the currents carried. The tower-footing resistance for towers 7,705 to 7,708 inclusive, in multiple, is found to be 179 ohms, from Table I, the combination tower and driven-rod resistance is found to be 2.89 ohms, and by calculation the driven-rod resistance alone is 2.93 ohms. Table IX shows that the driven rods carried about 81 per cent of the total current and the parallel continuous counterpoise about 17 per cent, with the tower-footing current negligible. The equivalent resistance of the parallel counterpoise is 13.7 ohms, compared with 2.9 ohms for the driven rods.

A buried probe conductor opposite tower 7,707 carried no measurable current, while the driven rods at this tower picked up 4,400 amperes.

Stroke 3

This stroke took place on July 30, 1940, to the overhead ground wire between towers 7,714 and 7,715, in section *C*, equipped with right-angle counterpoise and driven rods. The stroke was negative. All tower currents flowed upward and all rod and counterpoise currents flowed toward the towers. Table X summarizes the current collection by right-angle counterpoise and driven rods.

The multiple footing resistance of the 12 towers, 7,712 to 7,723 inclusive, from

Table VI. Tower Current, Stroke 1

Tower No.	Amperes			Total Current (Amperes)
	Leg 1	Leg 2	Leg 3	
7,664	8,000	1,600	1,600	11,200
7,665	11,700	8,500	4,000	24,200
				35,400
Estimated cross-member current 65 per cent				23,000
Total				58,400

Table VII. Counterpoise and Tower-Footing Current and Resistance, Stroke 1

	Current		Resistance (Ohms)
	Amperes	Per Cent	
Parallel counterpoise	25,170	43.2	8.66
Right-angle counterpoise	28,130	48.3	7.75
Tower footings	5,100	8.5	42.7
Total	58,400	100.0	

Table VIII. Counterpoise and Driven-Rod Current, Stroke 2

Tower No.	Counterpoise		Driven Rod
	Type	Amperes	(Amperes)
7,705	Parallel	1,000	1,000
7,706	Parallel	800	2,200
7,707	Parallel	200	4,400
7,708	Parallel	2,500	13,400
7,710*			4,200
7,711	Right angle	2,000	2,000
Total		6,500	27,200

* Not installed.

Table IX. Driven-Rod, Counterpoise, and Tower-Footing Current and Resistance, Stroke 2

	Current		Resistance (Ohms)
	Amperes	Per Cent	
Driven rods	21,000	81.1	2.93
Parallel counterpoise	4,500	17.3	13.7
Tower footings	340	1.6	179.0
Total	25,840	100.0	

Table X. Right-Angle Counterpoise and Driven-Rod Current, Stroke 3

Tower No.	Counterpoise (Amperes)	Driven Rod (Amperes)
7,712	2,000	1,800
7,713	2,500	6,300
7,714	8,900	12,000
7,715	10,900	30,000
7,716	6,000	6,600
7,717	2,000	2,500
7,718	2,500	1,800
7,719	2,000	1,600
7,720	2,000	1,000
7,721	2,000	1,500
7,722	2,000	1,000
7,723	3,100	1,000
Total	45,900	67,100

Table XI. Driven-Rod, Counterpoise, and Tower-Footing Current and Resistance, Stroke 3

	Current		Resistance (Ohms)
	Amperes	Per Cent	
Driven rods	67,100	59.0	0.86
Right-angle counterpoise	45,900	40.3	1.26
Tower footings	900	0.7	64.0
Total	113,900	100.0	

Table I, is 64 ohms, while the multiple resistance of the combined footings and ground rods is 0.85 ohm. From these figures the driven-rod resistance alone calculates 0 86 ohm.

Table XI shows the division of current and the equivalent resistance of the driven rods, right-angle counterpoise, and tower footings, on the assumption that the resistances are inversely proportional to the currents. From Table XI it will be seen that the driven rods carry about 59 per cent of the current and the right-angle counterpoise wires about 40 per cent, the tower-footing current being negligible.

From Table XI the summation of the currents picked up by the driven rods, right-angle counterpoise wires, and tower footings is about 114,000 amperes. The sum of all tower currents involved in the stroke, towers 7,712 to 7,723 inclusive, is 60,700 amperes, which increased by 65 per cent for estimated cross member currents, would give 100,000 amperes. This should be increased by 3,300 amperes coming in on the overhead ground wire from beyond tower 7,712. Thus there is good agreement between the current of about 114,000 amperes collected from the ground and the tower current of about 103,000 amperes. However, the current in the overhead ground wire at the two ends of the span that was struck totaled only 57,300 amperes. This current is undoubtedly too low. A saturated inner link at the Croton side, at tower 7,715, permitted the use of the outer link only, with the unidirectional calibration curve. This value is therefore a minimum. This discrepancy might indicate that the counterpoise and ground-rod current crests are not coincident. The currents in the counterpoise in the ground surface might rise to crest value more quickly than the currents in the ground rods, which are draining a charge from 100 feet below the surface, including the ground charge extending well out beyond the surface counterpoise wires.

It will be noted from Table X that, in the towers near the lightning stroke, the driven-rod currents are much greater than the counterpoise currents, while at the more remote towers the pickup is more nearly equal, if not greater in the counterpoise. This might be expected if the major portion of the ground charge is located deeply and flows through a conducting layer radially to the driven rods near the lightning stroke.

Summation of the counterpoise currents to the north of the line gave 30,000 amperes, while those to the south of the line totaled 15,900 amperes. This would suggest that the cloud charge participating in the lightning stroke was more to the north of the line.

A reading of 5,000 amperes was obtained in a buried probe conductor opposite tower 7,715, while in the three stations on the right-angle counterpoise wire, extending in the same direction, readings were obtained of 1,000, 2,500, and 3,400 amperes, going progressively toward the tower. Also a reading of 1,800 amperes was obtained in a probe conductor opposite tower 7,722, while a reading of 1,000 amperes was obtained in the right-angle counterpoise extending in the same direction at the magnet station nearest the tower.

Stroke 4

This stroke took place July 30, 1940, to the overhead ground wire of the *N*-14 line between towers 7,702 and 7,703, in section *B*, with parallel continuous counterpoise and driven rods.

The current collection for the parallel counterpoise and driven rods is shown in Table XII. The stroke was negative.

The resistance of the footings of towers 7,700 to 7,706 inclusive, in multiple, is 93.7 ohms from Table I. The combined resistance of tower footings and driven rods is 1.74 ohms and the calculated resistance of the driven rods alone is 1.77 ohms.

Table XIII shows the distribution of current among the driven rods, parallel counterpoise, and tower footings, and the equivalent resistance on the basis that the current divides inversely as the resistance. It will be noted that the driven rods carry 88 per cent of the total current, as against 10 per cent for the parallel counterpoise wires.

Table XII. Parallel-Counterpoise and Driven-Rod Current, Stroke 4

Counterpoise		Driven Rods	
Tower No.	Amperes	Tower No.	Amperes
Beyond 7,700	1,600	7,700	1,900
7,700 to 7,701	0	7,701	2,300
7,701 to 7,702	1,100	7,702	10,100
7,702 to 7,703	2,300	7,703	17,800
		7,704	7,100
		7,705	1,000
		7,706	2,000
Total	5,000		42,200

Table XIII. Driven-Rod, Counterpoise, and Tower-Footing Current and Resistance, Stroke 4

	Current		Resistance (Ohms)
	Amperes	Per Cent	
Driven rods	42,200	88.0	1.77
Parallel counterpoise	5,000	10.4	15.0
Tower footings	800	1.6	93.7
Total	48,000	100.0	

Buried probe conductors opposite towers 7,700 and 7,707 showed no readable current. The driven rods at tower 7,700 picked up 1,900 amperes and there were readings in the parallel counterpoise wire and in the tower legs at this tower. However, at tower 7,707 no readings were obtained in the driven rods, counterpoise wire, or tower legs.

Strokes 5 and 6

These strokes occurred on October 2 1941, to the overhead ground wire between towers 7,715 and 7,716, and between towers 7,720 and 7,721. This is the section of line equipped with right-angle counterpoise and driven rods (section *C*). Subsequent inspection showed flash marks on all three insulator assemblies at tower 7,721, but there was no tripout on this date. Both strokes were negative.

The current collection for the right-angle counterpoise and driven rods is shown in Table XIV.

The multiple resistance of the footings of the ten towers, 7,714 to 7,723 inclusive, from Table I is 76 ohms, and the multiple resistance of the combined driven rods and tower footings is 0.976 ohm. From these figures the resistance of the driven rods alone is 0.99 ohm. The distribution of current and the equivalent resistances are shown in Table XV. It will be noted that the driven rods carry

Table XIV. Right-Angle Counterpoise and Driven-Rod Current, Strokes 5 and 6

Tower No.	Counterpoise (Amperes)	Driven Rod (Amperes)
7,714	0	1,800
7,715	6,400	1,000
7,716	0	1,800
7,717	0	3,300
7,718	0	3,000
7,719	0	10,400
7,720	7,300	40,800
7,721	14,000	42,000
7,722	0	15,000
7,723	0	6,000
Total	27,700	124,800

Table XV. Driven-Rod, Counterpoise, and Tower-Footing Current and Resistance, Strokes 5 and 6

	Current		
	Amperes	Per Cent	Resistance (Ohms)
Driven rods	124,500	81	0.99
Right-angle counterpoise	27,700	18	4.45
Tower footings	1,620	1	76.0
Total	153,820	100	

about 81 per cent of the current, as against 18 per cent for the right-angle counterpoise.

No readable current was measured in buried probe conductors opposite towers 7,715 and 7,721. In the right-angle counterpoise wire, extending toward the probe wire at tower 7,715, 6,400 amperes were measured at the magnet station adjacent to the tower. In the right-angle counterpoise wire, extending toward the probe wire from tower 7,721, currents of 800, 3,600, and 5,800 amperes were read progressively toward the tower.

Voltage Gradient in Vicinity of Towers

For the purpose of indicating the voltage conditions in the vicinity of the tower during lightning strokes, a portion of the *T*-20 line was selected. This line runs between Croton and Grand Rapids, a distance of approximately 39.2 miles. The line has four-legged double-circuit steel towers, with the conductors arranged vertically on one side of the tower only for 32 of the 39.2 miles. The conductors are 110,000-circular-mil copper, with 15.1-feet equivalent delta spacing. One overhead ground wire, consisting of three strands of number 8 Copperweld, is installed at the peak. The line is insulated with ten disks, spaced $4^3/_4$ inches on suspension, and 12 units on dead ends. A section of this line from towers 4,387 to 4,417 inclusive, 31 towers, was selected for this investigation.

About two thirds of this test section traversed a sandy plain where tower-footing resistance was very high, while the remainder passed over low ground composed of muck and sand where footing resistances were comparatively low. Ten consecutive towers in the high-resistance section, 4,387 to 4,396 inclusive, were equipped with deep-driven rods to reduce the tower-footing resistance. In two cases there was one rod per tower, in five cases two rods per tower, and in three cases four rods per tower. The resistances of all the towers in the experimental section are given in Table II.

At one side of each tower, and about six feet from the tower legs, a probe rod was driven into the ground about five feet deep, and between the tower and the probe rod was introduced a lightning-stroke recorder.[6] The purpose of this recorder was to measure the voltage drop between the tower and the probe rod during lightning strokes.

Each tower leg was equipped with a bracket, and after 1937 a bracket was installed on the overhead ground wire on each side of each tower. Each deep-driven rod was also equipped with a bracket. In all cases each bracket was equipped with two magnetic links.

Eight strokes occurred on the *T*-20 line during the period of this investigation (1936 to 1941 inclusive). Six strokes in which there was good correlation between the tower current and the potential between tower and probe rod are summarized in Table XVI.

The stroke on September 15, 1936 (stroke 7) made contact with the overhead ground wire between towers 4,404 and 4,405. Measurements were obtained at 31 towers extending from 4,387 to 4,417 inclusive. At 29 towers, records were obtained on the lightning-stroke recorders connected between the tower leg and the five-foot probe rod. These readings ranged from 5 to about 50 kv, the external flashover value of the recorder. There were 3 cases of external flashover and 13 cases of film flashover. As a result of this experience, capacitance dividers with ratios of 2 to 1 were installed at all tower probe-rod stations.

On June 24, 1937, a stroke occurred to tower 4,408 (stroke 8). Records were obtained at 19 towers, 4,395 to 4,413 inclusive. In 7 cases the lightning-stroke recorder flashed over. For the other 12 cases, the readings ranged from 9 to about 100 kv, which was the flashover of the recorder and voltage-divider combination. It was therefore necessary again to increase the voltage-divider ratio and a 6 to 1 ratio was installed. This ratio proved sufficient, as no more flashovers were experienced.

All the strokes of which there were good records were negative. Stroke 12 is worthy of mention. This stroke (not listed in Table XVI) took place to the top of tower 4,389. About 6,300 amperes flowed upward in this tower, and a total of 6,300 amperes was measured in the two deep-driven rods connected to this tower, flowing upwards. In the adjacent tower 4,388, no current was measured, but in the second tower to the north, 4,387, about 13,200 amperes flowed downward and 6,000 amperes was measured flowing downward in the single deep-driven rod connected to this tower. Currents from the overhead ground wire flowed toward the stroke from beyond tower 4,387 and from beyond tower 4,391 to the south.

Surge Resistance of Tower Footings Under Natural Lightning Conditions

The potentials measured on the probe rods driven five feet deep at a distance six feet from the tower footings have been correlated with the tower-structure currents as shown in columns 4 and 6 of Table XVI. These tower-to-probe voltage measurements of column 6 are less than true tower potential by the earth potential differences beyond the probe rods. An approximation of the relation between measured tower-to-probe-rod voltage and actual tower potential is found as follows:

The current from the earth to the tower footing is assumed to be distributed uniformly in the earth, its density being the same at identical distances from the tower footing and inversely proportional to the square of the distance from the footing. The earth's resistance, being proportional to cross section, also is de-

Table XVI

(1) Stroke No.	(2) Tower No.	(3) R_N Tower-Footing Resistance (Ohms)	(4) I_T Total Tower Current† (Amperes)	(5) $R_N I_T$ Tower Potential (3)×(4) (Kv)	(6) V_M Tower-to-Probe Potential (Kv)	(7) V_T Tower Potential (6)×2.5 (Kv)	(8) R_S Surge Resistance (7)/(4) (Ohms)	(9) R_S/R_N (8)/(3) Ratio
7	4,394	35	6,000	210	27	67.5	11.2	0.32
8	4,410	15	3,300	50	5	12.5	3.8	0.254
9	4,408	75	11,700	876	190	475	40.6	0.542
10	4,400*	1,299	13,700	17,800	280	700	51.0	0.039
	4,401	942	6,800	6,400	170	425	62.5	0.066
11	4,394	35	6,600	230	40	100	15.1	0.432
	4,395	51	16,000	816	170	425	26.4	0.517
	4,396	56	11,000	617	140	350	31.8	0.569
13	4,412	13	45,600	592	222	555	12.2	0.939

* Flashover all three phases.

† Total tower current (column 4) assumed 1.5 times measured current in tower legs, to take care of cross member current.

creasing as the square of the distance from the tower footing.

The voltage gradient at ground points of differing distances from the footing will be inversely as the square of the tower to point distance. The potential at a ground point is the integrated voltage gradient and is therefore inversely proportional to distance.

Accordingly, with an assumed tower-base spread of 18 feet and a probe point 6 feet farther out, the probe potential will be to the tower potential as 9 is to 15, or the tower potential will be 15/9 times the probe potential. The tower potential less the measured tower-to-probe voltage will be the probe potential. Therefore, the measured tower-to-probe potential must be multiplied by 2.5 to give tower potential. Values of true tower potential calculated on this basis are given in column 7.

To show the relation between the surge resistance and the normal footing resistance, the values of column 9 were calculated by dividing values in column 8 by those in column 3. These figures show the surge resistance to range from some 4 to 90 per cent of normal resistance values. These values are somewhat lower than those reported from artificial surge measurements.[7,8] In this connection, however, it should be observed that the range of normal resistances, from 13 to 1,300 ohms, is wider than is ordinarily investigated, and the range of currents, 6,000 to 45,000 amperes, is also very wide. In general in these measurements we are dealing with high resistances and large currents.

The resistance ratio of column 9 was shown, by plotting, to decrease very definitely with increasing currents and with increasing resistances. Accordingly, this ratio was plotted against a composite factor the product of up-tower current and normal footing resistance shown in column 5. In Figure 2 the ratio of surge resistance to normal resistance of column 9 is plotted as ordinate against the product of current and normal footing resistance of column 5. The points, while somewhat scattered, nevertheless show very clearly the trend indicated by the solid line. This is borne out by plotting on log-log paper, which shows a relation between ratio and product as follows:

$$\frac{R_S}{R_N} = \frac{14}{(R_N I_T + 80)^{0.6}}$$

in which R_S = surge resistance, R_N = normal or megger tower-footing resistance, and I_T = total tower current.

For practical purposes these curves might be utilized somewhat as follows: Assume that it is desired to evaluate the surge resistance of a certain tower under a lightning current of 10,000 amperes, where a normal tower-footing resistance of 100 ohms has been measured. The product of tower current and footing resistance is $1{,}000 \times 10^3$, which referred to the curve gives a ratio of 0.22. This ratio applied to the 100-ohms footing resistance gives a surge resistance of 22 ohms. The resultant tower potential would be 220,000 volts, which is substantially below flashover.

The flashover of this line is taken as 700 kv on a 1.5x40-microsecond wave and on this basis it is interesting to examine actual field operating records as to insulator-assembly flashovers that might coordinate with the derived tower potential of column 7. Flashover occurred at tower 4,400 for stroke 10, for which the derived tower potential is just 700 kv. All three phases flashed over. No other flashovers are correlated with tower-to-probe measurements for the records shown in this table. Accordingly, on the basis of this flashover it is indicated that the ratio between true tower potential and measured tower-to-probe potential could not be lower than the 2.5 figure derived from the assumption outlined above. Also for tower 4,412, stroke 13, the tower potential is 555 kv, as the last item in column 7. In this case there was no flashover and the tower-to-probe potential was 222 kv. The ratio of 700 to 222 kv, or slightly over 3 to 1, is therefore indicated as the upper limit by these data. It is therefore concluded that the true ratio is between 2.5 and 3 to 1 and the use of the curve for interpreting true surge resistances from tower currents and normal ground-resistance measurements is seen to be reasonable.

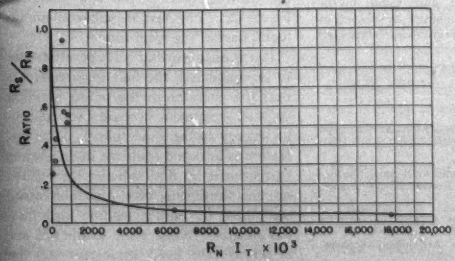

Figure 2. Ratio of surge resistance to normal tower-footing resistance, plotted against product of current and normal footing resistance during natural lightning strokes

Conclusions

In field lightning research, the investigators are often disappointed at the few direct strokes in the experimental section, even after a period of several years. The present investigation is no exception. However, it is believed that the preceding analysis and the following conclusions represent a fair interpretation of the limited data available. It should be understood that the conclusions apply specifically to the conditions prevailing on this particular transmission line.

1. Parallel continuous counterpoise wires and right-angle counterpoise wires of equal total length have approximately equal current-collecting ability. Direction of counterpoise apparently is not a governing factor, but only resistance to ground. In comparison with the normal tower footings the counterpoise wires are very effective in picking up lightning current.

2. In sandy high-resistance soil, rods driven deep enough to penetrate the clay or loam beneath the sand serve to reduce the tower-footing resistance from 500–1,400 ohms to 7–25 ohms. These rods, in comparison with counterpoise wires in the high-resistance surface soil, are much more effective in picking up lightning current.

3. There is some indication that the current pickup in the counterpoise wire near the ground surface and in the deep-driven rods is not coincident. Possibly the ground rod requires more time to discharge the surrounding earth on account of its deep penetration into the earth.

4. Data seem to indicate that the ratio of surge tower-footing resistance to normal tower-footing resistance decreases definitely with increasing currents and with increasing resistances. For example, at 10,000 amperes and 100 ohms the surge resistance decreases to approximately 22 ohms. This may account for frequent failure to flash over when the product of current and normal resistance indicated that flashover should take place.

5. The ratio of surge resistance to normal footing resistance is shown under natural lightning conditions to be as low as 0.04 for sandy soil, where normal resistance ranges up to 1,000 ohms or more and tower current up to approximately 50,000 amperes.

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Precision Speed Control for World's Largest Induction Motor

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FELLOW AIEE

A RECENT paper by Dickey, Kilgore, and Laffoon described an installation consisting of a 40,000-horsepower wound rotor induction motor and the necessary auxiliary equipment required to provide for variable speed operation.[1]

To meet the many requirements of control, imposed by this application, it was necessary to devise new methods for insuring smooth acceleration of auxiliaries and main motor, for limiting the change in power required from the supply system to a definite maximum value, to provide precision regulation of speed, as well as means for control for the main motor from either of two points. In addition, power-factor regulation and means for emergency quick stopping was provided. These and many other features were incorporated in the automatic control, the functions of which are briefly outlined in the following paragraphs.

In order that the auxiliary motor generator sets and main motor may be supplied with adequate bearing lubrication and ventilation at all speeds, it is necessary to start the oil circulating pump and ventilating fans prior to placing those units in service. In addition, the seven-unit exciter set, which supplies d-c energy to the fields of the machines comprising the auxiliary motor-generator sets, must be started. After these preliminary operations are complete, the starting indication is given the automatic control by manual operation of the starting control switch which energizes the master relay. Starting and acceleration of the auxiliary motor-generator sets and connection of the main motor to the 6,900-volt bus is accomplished in the following sequence:

1. Closing of d-c machine field breakers.
2. Closing of high-voltage breaker for constant speed motor-generator set, energizing motor through starting reactor.
3. Closing of starting reactor short-circuiting breaker.
4. Energizing of fields of a-c machines.
5. Connection of speed matcher to bus and primary of main motor.
6. Acceleration of variable speed motor-generator set under control of constant current regulator for d-c machine fields and master speed-control rheostat operated by speed matcher contacts.
7. Energizing of voltage-balancing relay and automatic synchronizer.
8. Closing of main motor primary breaker.

At this point the main auxiliaries are operating at synchronous speed and the main motor is at rest but connected to the 6,900-volt three-phase bus. To start the main motor the operator, at one of the two suitably interlocked control points, turns the pointer on the speed-control dial to a definite speed position. Following that manual operation the automatic control completes the following operations:

1. Starts rotor-lift oil pumps for main motor.
2. Causes the variable speed set to slowly decrease in speed.
3. Main motor begins to rotate and gradually approach the desired speed.
4. Acceleration stops and main motor speed is maintained constant by means of the electronic speed regulator, controlled from a pilot generator on main motor. This regulator provides energy for speed-regulating field windings on d-c machines of constant speed motor-generator set.

In stopping the main and auxiliary units, the automatic operations take place in the reverse order to those performed when starting. The same smooth operation is afforded, as in starting, with power being fed back into the system as a means of decelerating the machines.

All of the recent developments in switching equipment were employed to provide utility, flexibility, and compactness of design. The 6,900-volt switchgear is of the metal-clad type, using oil circuit breakers having a suitable interrupting capacity; all low-voltage circuits are protected with metal-enclosed air circuit breakers, and the main control switchboard is of duplex construction. In addition to all those features, the latest innovation in relay construction was employed by the use of plug-in devices for both protection and automatic control.

Starting of Auxiliaries

All of the power and switching equipment, consisting of the following apparatus, is located in the power building (Figure 2).

1. 40,000-horsepower main motor.
2. 6,250-kva constant-speed motor-generator set.
3. 38,000-horsepower variable-speed motor-generator set.
4. 400-horsepower seven-unit exciter set.
5. 6,900-volt metal-clad high-voltage switchgear.
6. 460-volt metal-enclosed switchgear.
7. Seven-panel main duplex control switchboard.
8. Ventilation blowers for main motor and each motor-generator set.
9. Lubricating-oil circulating equipment.

Apparatus for remote control of the main-motor speed and for emergency quick stopping is installed on a control desk in the control room of the test chamber, Figure 3. The test chamber is an integral part of the wind tunnel.

If it is assumed that test operations are to be conducted, the first requirement is that the operator in the power building start all equipment necessary for supplying energy to the wind tunnel. This operation is initiated from the main control switchboard by first starting the exciter set, the ventilating fans, and lubricating equipment by remote manual push-button control. When these auxiliaries are in service, the main auxiliaries may be

Paper 42-132, recommended by the AIEE committees on air transportation and electrical machinery for presentation at the AIEE summer convention, Chicago, Ill., June 22-26, 1942. Manuscript submitted April 20, 1942; made available for printing May 21, 1942.

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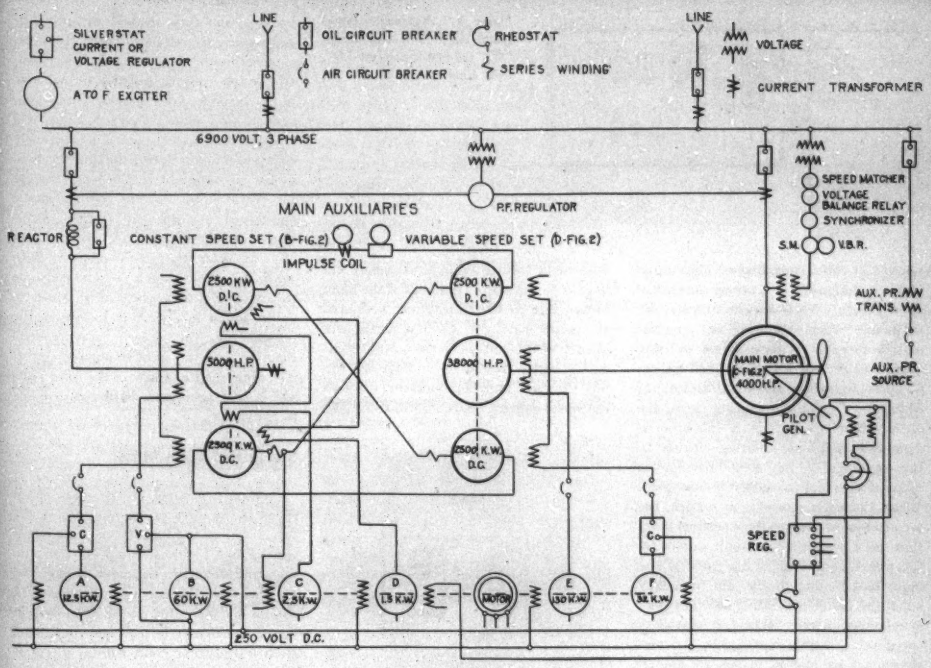

Figure 1. Schematic connection diagram for 40,000-horsepower motor and auxiliaries

started by means of a control switch on the main control switchboard. This switch energizes the master relay of the automatic control and all further starting operations are accomplished under the supervision of that equipment.

Starting of Constant-Speed Motor-Generator Set

The constant-speed motor-generator set consists of a 6,250-kva a-c machine and two 2,500-kw 750-volt d-c machines. During the starting operation of both main auxiliary sets, the a-c machine functions as a synchronous motor, and the d-c machines as generators. After the 40,000-horsepower motor is in service, the d-c machines operate as motors driving the a-c machine as a synchronous generator supplying power to the a-c system. Because of the dual function of these machines and to avoid confusion, they are referred to simply as a-c and d-c machines rather than as motors or generators.

Each operation, in the starting scheme, follows a planned automatic sequence which insures correct and positive functioning of the equipment being controlled. Following energizing of the master relay, the automatic control closes the field breakers for the fields of the d-c machines of both main auxiliary sets. Completion of this operation, as indicated by interlocks on the field breakers and a contact on the field relay for the d-c machines of the variable-speed set, the a-c machine of the constant-speed set is connected to the 6,900-volt bus through a starting reactor.

During the time that the constant-speed motor-generator set is accelerating, excitation on the exciter for the d-c machines of this set is held at zero. After sufficient time has elapsed for the set to reach approximately synchronous speed, a reactor short-circuiting breaker is closed connecting the a-c machine directly to the bus. This operation is followed by application of field energy, and the motor-generator set then pulls into synchronism and is ready to assume the load required for starting the variable-speed unit.

Master Speed-Control Rheostat

Because of the necessity for simultaneous control of all d-c-machine fields when initiating speed changes, it was necessary to combine all field rheostats in a motor-driven master speed-control assembly. This master rheostat is comprised not only of rheostats for exciter field control, but rheostats for recalibrating the Silverstat constant current regulators used in the fields of the d-c machines of the main auxiliary sets. In order to assure correct commutation on the d-c machines of the variable-speed set at all loads, shunt rheostats connected across those commutating fields are included in the master assembly. Also, this assembly contains a recalibrating rheostat for the electronic speed regulator, as well as one for controlling the field current to the driving motor of the master speed-control rheostat. This latter rheostat is used to provide for slow operation of the entire assembly when the variable-speed set or main motor is being accelerated, or decelerated, thereby assuring a slow and uniform change in power on the system.

Starting of Variable-Speed Motor-Generator Set

The variable-speed motor-generator set consists of a 38,000-horsepower synchronous machine and two 4,000-horse-

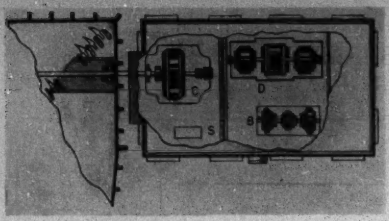

Figure 2. Automatic-control switchboard "S", main motor "C", variable-speed set "D", and constant-speed set "B"

power 750-volt d-c machines. The a-c machine is designed for a stator current of approximately 5,000 amperes at 5.5 cycles frequency when operating at approximately 48 rpm. This machine will also operate at a stator voltage of 4,800 volts at 60 cycles frequency and when rotating at 514 rpm. During the starting period the a-c machine operates as a synchronous generator supplying exciting current to the windings of the 40,000-horsepower main-motor rotor to which it is connected. When the main motor is in service, the a-c machine of the variable-speed set functions as a synchronous motor driven by the power generated in the rotor of the main motor—due to the slip frequency when the motor is rotating at other than synchronous speed. When the variable-speed set is being started, the d-c machines act as motors driven by energy from the d-c machines on the constant-speed set. After the main motor is in operation, these same d-c machines function as generators, driven mechanically by the a-c machine, and supply power to drive the constant-speed motor-generator set which feeds power into the a-c system. Had the conventional means of speed control been used, this power would have been dissipated as heat and been lost.

During the starting operation of the variable-speed set, the master speed-control rheostat is under control of a balanced torque-type speed matcher. The elements of the speed matcher are connected to potential transformers on either side of the open contacts of the main-motor primary breaker. Initially with the variable-speed set at rest, there is no voltage on the stator or primary terminals of the main motor, and the speed-matcher element connected to the bus side of the breaker operates to close a contact to cause the master speed-control rheostat to operate. The rheostat will function to permit excitation of the fields of the d-c machines of the constant-speed set, and those machines will deliver energy to the d-c machines on the variable-speed set. As this set begins to rotate, the a-c machine will generate a voltage and frequency proportional to the speed. An equivalent voltage at equal frequency will appear on the stator terminals of the main motor, due to the transformer action of the motor windings. So long as the frequency of the voltage on the motor terminals is below that of the voltage on the bus, the speed matcher, operating through the speed-control rheostat, will cause the

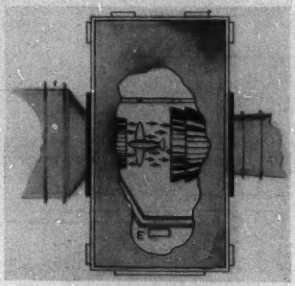

Figure 3. Remote-control desk "E"

variable-speed set to accelerate. Acceleration is accomplished first, by increasing the field strength on the d-c machines of the constant-speed set to a maximum and, finally, by decreasing the field current in the d-c machines of the variable-speed set until synchronous speed is reached.

Connection of Main, 40,000-Horsepower Motor to Bus

In order that power drawn from the power-supply system may be a minimum when the main motor is connected to the bus, the voltage on the stator windings is synchronized with the bus voltage before the oil circuit breaker is closed. This synchronizing operation is accomplished by means of an electronic-type automatic synchronizer operating in conjunction with the speed matcher and a voltage-balancing relay. At the instant that synchronism is accomplished, the oil circuit breaker is closed automatically.

All operations of the speed matcher, synchronizer, and voltage-balancing relay cease with closing of the main-motor breaker, and these devices are automatically removed from the circuit. However, a power-factor regulator takes over control of the excitation of the a-c machine of the variable-speed set, and through operation of a motor-operated shunt field rheostat functions to maintain practically unit power factor during the time the main motor is connected to the bus. Except for power-factor control the automatic equipment performs no further operations until the indication is given manually to start the main motor. Both auxiliary motor-generator sets continue to rotate at synchronous speed, since no device is yet in operation to change the position of the master speed-control rheostat, and the main motor remains at rest while the frequency of the rotor voltage is in synchronism with that applied to the stator.

Starting of Main Motor

Normally, control of the main motor speed is the duty of the operator in the test chamber, and for this reason, a speed-control dial, Figure 4, equipped with contacts and a synchro-tie motor, is mounted on the test-chamber control desk. A similar dial is located on the main switchboard, but it may be assumed that speed control from that point will be an emergency operation in the event that a fault occurs in the control cable between the power building and the test chamber. Control assignment switches are located

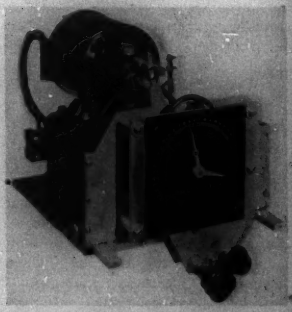

Figure 4. Speed-control dial, contact mechanism, and Synchro-tie

beside each control dial for the purpose of assigning control to either, but not both, locations. Assignment of the point of control is accomplished by both assignment switches being in agreement, and, after once being assigned, cannot be changed by either one of the operators

changing the position of his switch. A set of indicating lamp signals, coupled with the assignment switches, indicate the point to which the control has been assigned, and also indicate when the assignment switches are not in agreement.

With the main motor connected to the bus, but at rest, the operator to whom control is assigned may cause the motor to start and assume a certain definite speed by merely turning the knob on the control dial until the pointer reaches the desired speed position. It is well to note that the automatic control is provided with a position indicating relay, so that if the speed-control dial is not at the zero speed position when the main motor is connected to the bus, it will be necessary for the operator to return the pointer to zero and then to the desired speed setting before the motor will start. This insures that the motor will remain at reset after being connected to the bus during the starting operation, even though the control dial is at other than the zero speed position. Movement of the pointer off the "zero" speed position will cause the starting of rotor-lift oil pumps which will raise the main-motor rotor off the bearings, and when this is accomplished, the speed control equipment will operate to start the motor.

Acceleration of the main motor is accomplished by gradually slowing down the variable-speed set by first strengthening the field of the d-c machines on that set, and, as the speed decreases, by weakening the fields of the d-c machines on the constant-speed set. These field changes are accomplished by means of the master speed-control rheostat. This rheostat is equipped with a synchro-tie motor which is coupled electrically to a similar motor on the speed-control dial mechanism. When rheostat and dial mechanism are in the same relative position, with respect to main-motor speed setting, contacts on the dial mechanism are closed, short-circuiting the operating coils of the polarized "raise-lower" relay which is a part of the speed-control apparatus. Moving the dial mechanism to some fixed speed position opens these contacts, and the polarized control relay operates to cause the master rheostat to operate in a direction which will increase or decrease the main-motor speed, depending upon which way the dial pointer is turned. As the rheostat moves to accomplish the desired speed change, the synchro-tie moves a contact on the dial mechanism. When the rheostat reaches the position which will cause the motor to operate at the new speed setting, the control contacts will again close, and the rheostat will stop.

Control of Motor Speed

After the master speed-control rheostat comes to rest, the control for constant speed of the main motor is taken over by an electronic speed regulator which receives control energy from a pilot generator geared to the motor shaft. This speed regulator is recalibrated for any new speed setting by means of a rheostat on the master speed-control rheostat assembly. The regulator energizes the field of a small 1.5 kw speed-control exciter which supplies energy to field windings on the constant-speed machine. By increasing or decreasing the shunt field strength of this machine, the speed of the main motor is held constant by varying the torque through control of the power taken from the rotor and fed back into the a-c system.

By varying the speed of the speed-control rheostat automatically, smooth acceleration and deceleration of the main motor is possible. Also, by this means, the amount of power drawn from the bus during acceleration may be held to a steadily increasing value not exceeding a fixed increase per minute at any point on the speed range between 0 and 295 rpm. When the desired speed is reached, the electronic regulator maintains that speed constant within a range of 0.5 per cent for speeds from 37.5 rpm to 150 rpm and 0.3 per cent between 150 and 295 rpm.

Stopping of Main Motor and Motor-Generator Sets

The normal method for stopping the main motor and auxiliaries is first to reduce the main-motor speed to zero, then trip the motor breaker by turning the "start–stop" control switch to the "stop" position. Tripping of this breaker will disconnect the motor from the bus, and the automatic control will operate to decelerate the variable-speed set and cause it to come to rest. When this set is at rest, the high-voltage breaker for the power supply to the constant speed a-c machine will be tripped, and all automatic equipment will assume a normally de-energized position in readiness to again start the units at the will of the operator.

Emergency Quick Stopping

Means is provided for rapid deceleration of the main motor in case of emergency and, under such conditions, the motor is decelerated at the most rapid possible rate permitted by the power company. Rapid deceleration will cause power to be fed into the power company's system by regeneration through the main auxiliary motor-generator sets. Means is also provided for emergency shutdown and disconnection of all units from the bus should the necessity arise. Under this condition, all high-voltage and field circuit breakers are tripped simultaneously, and the main motor and motor-generator sets drift to standstill with friction and windage losses being the only decelerating forces.

Protective Devices

A complete complement of protective relays is provided with the automatic control. Those devices which prevent starting or operate an annunciator and sound an alarm are as follows:

1. Failure of bearing oil flow.
2. Failure of ventilation air.
3. Low lubricating oil pressure.
4. Low a-c voltage.

Those devices which merely annunciate and sound an alarm are:

1. High machine winding temperature; all machines.
2. High lubricating oil temperature.
3. Low lubricating oil temperature.
4. High bearing temperature.
5. Basement air temperature.
6. Low lubricating oil level.
7. Ground on auxiliary power circuits.

Devices which operate a lockout relay, drop an annunciator, sound an alarm, and cause all machines to be immediately removed from service are:

1. Overspeeding of either main auxiliary motor-generator set.
2. Unbalanced phase current on constant-speed a-c machine or main motor.
3. Differential protection on constant speed a-c machine or main motor.
4. A-c overcurrent in constant speed a-c machine or main motor.
5. Low a-c voltage on the bus.
6. Failure of unit to complete automatic starting sequence.
7. Overcurrent on d-c machines of main auxiliaries.
8. Short circuit on d-c machines of main auxiliaries.
9. Manual operation of emergency stopping switch.

The more serious of these faults, as indicated, cause immediate disconnection of the units from the bus while others merely sound an alarm and warn the operator that continued operation is undesirable, at which time provisions can be made to complete the test in as short a time as

Electrical Features of Design and Operation of the Plantation Pipe Line

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PLANTATION Pipe Line Company's new 1,254-mile pipe line system is the largest ever built for the handling of refined petroleum products and is the largest all-electric-powered pipe line in existence. First full-length delivery was made early in February 1942, and immediately the line became an important factor in the transportation of gasoline and fuel oils to a large area in the southeastern states. Compared to the usual pipe line, this system operates under highly exacting conditions, and in its design the electrical and associated control features are of prime importance. The major electrification problems were:

1. To design for economical future increase in line capacity.

2. To provide flexibility in operation to meet varied schedule requirements.

3. To co-ordinate pumps, motors, and control, so as to accomplish the starting of units reliably and with reasonable demand on the station power service.

4. To design stations for safe handling of petroleum products.

5. To develop a station control system, co-ordinating the electric and hydraulic-control devices and meeting the requirements of single-attendant operation.

Paper 42-143, recommended by the AIEE committee on industrial power applications for presentation at the AIEE summer convention, Chicago, Ill., June 22–26, 1942. Manuscript submitted April 13, 1942; made available for printing June 1, 1942.

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The authors wish to acknowledge the collaboration of R. A. Rockwell, engineer, Mason Neilan Regulator Company, and of A. Hollander, consulting engineer, Byron Jackson Company, in the development of the hydraulic control system discussed in a portion of this paper.

General Conditions of Operation

The statements made in this report regarding the capacities, pressures, and horsepowers, both for present operation and future installation possibilities, do not necessarily represent actual conditions, but do indicate the general principles involved.

The system comprises an unloading dock at the supply terminal with a short line of four parallel 12-inch pipes to a storage tank farm and the initial station of the pipe line proper, a section of 12-inch line, followed by a section of 10-inch line extending to the delivery terminal. Four branch lines serve areas to the north and south of the main line. The tankage at the supply terminal main line station is used to store incoming shipments, and to make up pipe-line shipments (known as tenders) according to the system schedule. Smaller storage facilities are located at the branch line origins.

Approximately 30 delivery terminals are situated at various points along the system, each with facilities for handling several products. The handling of multiple products to 30 delivery points creates a scheduling and dispatching problem probably far more complex than on any existing line.

The capacity of the line as initially equipped is 60,000 barrels per day of gasoline through the 12-inch section and 42,000 barrels per day through the 10-inch section. This requires two 600-horsepower motor-driven main-line pumps for each of the seven stations on the 12-inch line, and two 450-horsepower units in each of the seven stations on the 10-inch line. Each of three branch lines is served by a single 150-horsepower unit. A 450-horsepower unit is required at the origin of the fourth branch line, plus an additional booster station requiring a single 450-horsepower unit. The unloading station at the supply terminal dock contains five 600-horsepower units, providing ample capacity for rapidly unloading two tankers simultaneously. The initial mainline station at the supply terminal tank farm contains a complete spare pump unit to insure the availability of two units at all times. The system comprises 16 stations with a total of 39 centrifugal pumping units exclusive of tankage pumps and auxiliary pumps.

Provisions for Future Increase in Capacity

The present installation is designed as a long-term project to cover the commercially possible. All of the above protective features may be incorporated in the control of different types of machines but, never before, have all been included in the protection of a single assembly of machines.

Switchgear

The high-voltage metal-clad switchgear is equipped with lift-type oil circuit breakers which may be easily removed for inspection and service. Low-voltage metal-enclosed switchgear makes use of drawout-type air circuit breakers of suitable interrupting capacity for the circuits involved. The control switchboard is of the duplex type with meters and control switches on the front panels and all automatic and protective relays on the rear panels. Meters are semiflush, and all relays are semiflush of the plug-in type, equipped with stab contacts which permit easy removal from the panel for inspection and calibration. The entire assembly is easily accessible for maintenance and service, and all parts are of most advanced design with formed steel switchboard panels assembled in a complete self-supporting structure.

Conclusion

The automatic control provides reliable means, by use of proved apparatus, for performing all of the necessary starting, stopping, speed control, and protective functions for equipment of the type and size employed. The various switchgear assemblies are compact and well adapted to the service.

Many new switching problems were encountered in designing the complete control, and their solution opens up new fields of application to other apparatus. In addition, different types of standard equipment were employed to provide a complete and modern design which can be easily duplicated and one in which spare or renewal parts are readily obtainable.

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Figure 1. Pump room of typical main-line station on Plantation Pipe Line system

cial needs of the territory served and to operate economically on that basis. At the same time provision is made for possible future operation at increased capacity.

The maximum pressure at which the line will be operated is approximately 900 pounds per square inch in the 12-inch section and 975 pounds per square inch in the remaining sections. These values are determined by the allowable unit stress in the pipe walls, which in turn is a matter of economics in the design of the line. It is necessary in centrifugal pump operation that positive suction pressure be maintained at each pump, and if the minimum allowable suction pressure at the initial pump is established as, say, 40 pounds per square inch, then with a maximum allowable station discharge pressure of 900 pounds per square inch, the pressure increment introduced into the line at any station is 860 pounds per square inch, plus the pressure loss through the station piping. The stations are so spaced, then, that the pressure drop between stations due to fluid friction at rated line throughput, plus the static pressure differential totals approximately 860 pounds per square inch. Between the discharge of one station and the suction of the next, with uniform pipe, there is a uniform decrease in the component of total pressure due to line friction, this pressure drop being directly proportional to the distance from the upstream station. Referring to Figure 2, which represents a level section of 12-inch line, *SA* represents the suction pressure at initial station *A*, *DA* the discharge pressure at this station, and line *DA-SB* the pressure gradient along some 60 miles of line from station *A* to station *B*, for a flow rate of 60,000 barrels of gasoline per day. This is the flow that can be carried by the line under the conditions prescribed. If station *B* is at an elevation higher than station *A*, the distance between stations must be decreased by an amount that will reduce the friction drop sufficiently to provide the pressure differential necessary to balance the positive static head, and if station *B* is lower than station *A*, the distance between them will be increased to compensate for the negative static head.

To increase the capacity of the line without exceeding the maximum allowable working pressure, a second series of intermediate pressure increments may be added, one of which is represented by intermediate station *M*. If this station is placed at the hydraulic mid-point between stations *A* and *B*, the same pressure increment may be introduced at station *M* as at station *A*. The flow rate then will increase to a value such that the pressure drop between stations *M* and *B* will be the same as existed between stations *A* and *B* before adding the pressure increment at *M*. For the line in question this flow rate for gasoline is calculated at approximately 90,000 barrels per day.

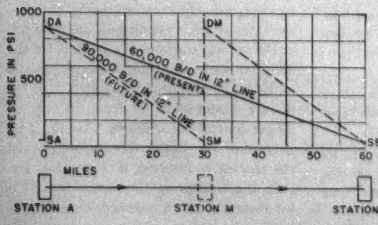

Figure 2. Pipe-line pressure gradients for flows of 60,000 barrels per day and 90,000 barrels per day

When this higher flow rate is established, obviously the horsepower input per station must be increased in both the initial and added stations. Whereas the initial stations are equipped with two 600-horsepower units for 60,000 barrels per day throughput, operation at 90,000 barrels per day will require two 900-horsepower units in all stations.

All stations on the main line are arranged for future change-over to higher capacity by initially installing pumps of such design that new impellers can be readily substituted, and motors designed for ultimate operation at the increased horsepower. These motors are of the totally enclosed fan-cooled type, and in order to secure efficient operation of the 12-inch line motors at 600 horsepower, they are equipped initially with a ventilating fan designed to deliver only the amount of ventilating air required by the motor operating at this capacity; when the change-over to 900 horsepower is made, no electrical or mechanical changes are involved except replacement of this one fan on the front shaft extension. Similarly, on the 10-inch section of the line, motors of ultimate 600 horsepower capacity are installed with initial fan capacity for operation at 450 horsepower. The motor-control and power-supply equipment in all the main-line booster stations are designed for operation at the ultimate ratings.

Operating Flexibility

All motors 75 horsepower and above are 2,300 volt. All motors above 150 horsepower are 3,600 rpm. All motors 450 horsepower and above are mechanically interchangeable, simplifying the problem of spare equipment, because a spare motor of 600/900-horsepower design can be installed on any line pump unit in the system except the 150-horsepower branch-line units. This feature also provides maximum utility of the equipment under unpredictable future alterations, due to changed operating conditions.

While the line is designed for a certain rated capacity, consideration must be given also to its flexible and economical operation at reduced throughputs. Contrary to practice on lines handling one uniform type of tender, the throughput of this line must be held above a certain minimum rate, to prevent excessive contamination between adjoining tenders

passing through the line. Between this rate and the full capacity of the line it is desirable, from the standpoint of power consumption, to operate at a rate as low as will suffice to meet the transportation schedules.

Motors of the constant-speed type are preferred because of their simplicity and their adaptability to construction suitable for hazardous atmospheres. Installation of two units per station, operated at constant speed, with the pumps connected in series, provides the required degree of flexibility. With this arrangement, and with all stations along the line having piping installed to permit by-passing any unused unit or station, changes in throughput in steps of a few per cent can be made by operating 2, 1, or 0 units in properly selected stations.

Motor-Starting Conditions

With the station locations determined solely by the hydraulics of the line and, therefore, without regard to existing power facilities, it was necessary to consider carefully the method of starting the units, from the standpoint of voltage conditions on the electric service.

Most stations contain two main pumps comprising 95 per cent of the station load. From the standpoint of starting conditions the 12-inch line motors are 900 horsepower, and the 10-inch line motors 600 horsepower. The motors are of low-starting torque design in order to minimize rotor resistance and attain high operating efficiency, important in view of the high load factor at which the system will operate. To minimize current peaks during starting, motor starters for all units 450 horsepower and above are of the autotransformer type, with closed-circuit transition. During the brief interval when the motor is transferred to full voltage with its terminals still connected to the starting tap, a reactor is inserted between the autotransformer tap and the motor to limit the current in the autotransformer circuit. By suitable control this reactor also provides an additional reduced-voltage starting step when power is first applied to the motor.

During starting, the discharge valve of the centrifugal pump is closed which minimizes the required motor torque. After the unit is up to speed the discharge valve is opened slowly so that the change in direction of flow through the station piping will be gradual, for well-known hydraulic reasons. Speed-torque curves for the pump with closed discharge, and for the motor with various applied voltages, are shown in Figure 3. These curves apply to the 12-inch line pumps when equipped with impellers for 900-horsepower operation, representing the most difficult conditions that must be met. The speed-torque requirements of the pumps are shown as a band curve, the upper limit applying to the pump when operating on fuel oil of specific gravity 0.83 and the lower limit for gasoline of 0.73 specific gravity.

Motor speed-torque curves and line current-torque curves are shown for full voltage, also for 80 per cent voltage applied by autotransformer. Also shown are speed-current curves for three-step starting with the reactor initially connected between the autotransformer tap and the motor. With the reactor in circuit approximately 85 per cent of the tap voltage appears at the motor terminals during the first portion of the initial starting step.

During starting, the voltage actually applied to the motor terminals should be of sufficient value to enable the motor to develop the torque necessary to reliably accelerate the unit to a speed above pull-out on the starting tap; when this speed is exceeded, the current decreases rapidly, and transfer to full voltage can be made on a low-current portion of the motor current-torque curve. Acceleration occurs directly as the excess of motor torque beyond pump input torque and inversely as the total inertia of the unit. Starting must be accomplished within a reasonable time, a limit in the order of 30 seconds being established as desirable by considerations of heating of the fluid within the pump casing. To perform the accelerating duty within this time limit it is found that the speed-torque curve of the motor when operating from the autotransformer tap should not fall below the curve corresponding to an applied voltage of about 1,630 volts. This means, when accelerating with the motor on tap giving a voltage of 80 per cent of line voltage, and with the reactor shunted, the voltage supply to high-voltage side of the starting autotransformer must be not less than:

1,630 volts ÷ 0.80 = 2,038 volts, or 88.6 per cent of normal 2,300 volts

Using a starting tap giving 85 per cent of line voltage, the voltage supply to the starting equipment must be not less than:

1,630 volts ÷ 0.85 = 1,918 volts or 83.4 per cent of normal 2,300 volts

To accommodate both present and future pump requirements, as well as variations in voltage conditions encountered at the several stations, the starters for the 600/900-horsepower motors were equipped with autotransformers having taps to deliver, under starting load, 80, 85, or 90 per cent of line voltage. In the first portion of the initial starting step, when the reactor is inserted into the tap circuit, the voltage at the motor terminals for these three tap connections is respec-

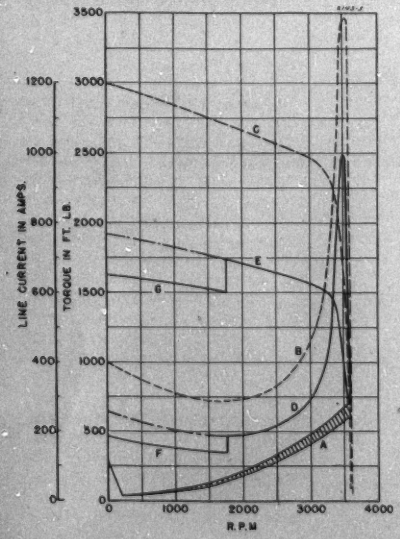

Figure 3. Starting characteristics of motor-driven pump on 12-inch line

A—Speed-torque for pump starting with closed discharge

B—Speed-torque for motor starting on 100 per cent voltage

C—Speed-line current for motor starting on 100 per cent voltage

D—Speed-torque for motor starting on 80 per cent voltage autotransformer tap

E—Speed-line current for motor starting on 80 per cent voltage autotransformer tap

F—Speed-torque for motor starting on 80 per cent voltage autotransformer tap with series reactor

G—Speed-line current for motor starting on 80 per cent voltage autotransformer tap with series reactor

tively, about 68, 72, or 76 per cent of normal line voltage.

Station Design as Affected by Hazardous Nature of Tenders

Safety problems introduced by the handling of petroleum hydrocarbon products of volatile and inflammable nature required special consideration throughout the design of the stations.

The areas subject to the occurrence of hazardous atmospheres (class *I*, group *D* as defined in the National Electrical Code) are the pump room and adjoining piping platform. The pump room contains the pumps with associated valves, hydraulic control devices, and piping. On the piping platform are situated the incoming and outgoing line piping and all necessary station and auxiliary piping with associated scraper traps, strainers, filters, valves, a sump tank with motor-driven pump for its service, and in many stations pressure-reducing valves and fluid meter and meter calibration facilities for delivery of product from the line to the distribution terminals.

The pump room is ventilated by a flow of incoming fresh air through glass-wool filters below the windows in the front wall of the station and directly opposite the motor air intakes. This air is forced through the motors by the motor blowers and discharged toward the rear wall of the pump room. In the rear wall just below the ceiling are mounted one or more motor-driven exhaust fans which discharge the air from the pump room and onto the piping platform. The piping platform is open on three sides with a flat roof for weather shelter, a construction affording maximum natural ventilation. The piping platform and pump room are at ground level, and in their design trenches and other depressions favorable to accumulating hydrocarbon vapors were avoided.

Figure 5. Outdoor substation for pumping station serving main and two branch lines

44- to 2.3-kv transformer bank consists of three 833-kva units. At right is the outdoor breaker controlling the 2,300-volt underground circuit to the pumping station bus. Structure at right mounts transformers for lighting, outside auxiliaries, and metering, as well as low-voltage breakers for lighting and outside auxiliary circuits

All electric motors, control, signal devices, motor-operated valves, lighting fixtures, and wiring installation in this area are specifically designed for service in class *I* group *D* hazardous atmospheres.

The 600/900-horsepower motors on the 12-inch line pumps are believed to be the largest, explosion-resisting motors ever built. Attainment of this rating in a relatively compact construction—an important consideration in explosion-resisting design—is accomplished by the circulation of large volumes of cooling air through the motor frame and by the use of class *B* insulation with the motor rating based on 75 degrees centigrade rise. All main-line pump motors have sleeve bearings, oil-ring lubricated and cooled by air blast from the motor ventilating fan. These bearings require no oil circulating system; consequently each motor is an entirely self-contained unit without external accessories.

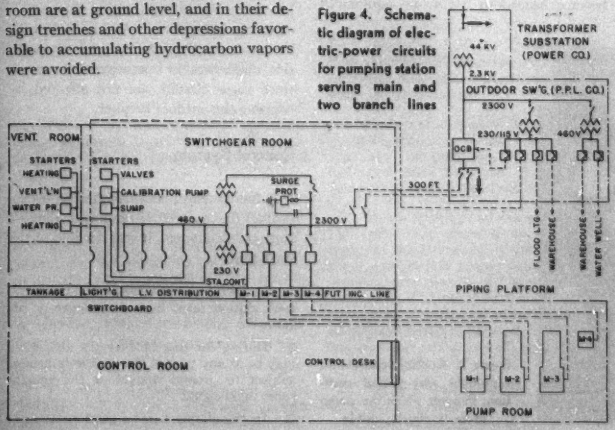

Figure 4. Schematic diagram of electric-power circuits for pumping station serving main and two branch lines

Control apparatus is of dead-front construction. With appropriate measures taken for safety, experience in products pipe-line operation indicates that provision of a nonhazardous location and installation therein of switchgear and control apparatus of open design are preferable to the use of special forms of switchgear and control in explosion-resisting or oil-immersed enclosures designed for class *I* group *D* location. This is true from both cost and operating standpoints. The importance of accessibility hardly can be overemphasized; since the several stations on a pipe line operate in series and interdependently, it is imperative that during operation of the line any inspection and maintenance work on electrical equipment be performed without shutdown or in emergency with the very minimum of shutdown time.

Nonhazardous conditions are maintained in all parts of the pumping station

Figure 6. General view of pump room showing two main-line pumps (left) and branch-line pump (right) driven by 450/600-horsepower explosion-resisting motors

building, except the pump room and piping platform. The nonhazardous portion of the building, designated as the operating section, has a floor level about three feet higher than the pump-room floor and is completely separated by wall from the pump room and piping platform. No direct connection is provided between these areas, it being necessary to pass through outside entrances in going from one to the other. The atmosphere in the operating section is maintained in safe coudition by outside air drawn into the building at the end opposite the pump room, maintained at a pressure a few inches above the outside air and above the atmosphere in the pump room. This insures that any air seepage through the wall, separating the operation section from the pump room or piping platform, will be in the direction to prevent entrance of hazardous atmosphere to the operating section.

The operating section of the station comprises a control room, switchgear room, ventilating and auxiliary room, lavatory, and in three of the stations a division superintendent's office.

The wall between the control room and the pump room consists of a vapor-tight, wire-glassed observation window. Into the center section of this window is sealed a vapor-tight steel gauge board, on which are mounted hydraulic recording and control devices and indicating pressure gauges as will be discussed later. These devices are gasketed to prevent passage of vapor through the mounting openings.

To provide for safely shutting down the station in case the control room should become hazardous due to an equipment failure, an explosion-resisting "emergency" pushbutton is mounted on the control desk contiguous to the gauge board. By pushing this button the attendant will trip the circuit breaker at the origin of the incoming power feeder.

This breaker, normally controlled from the incoming line panel in the station, is located at the transformer substation approximately 300 feet from the pumping station. From the outdoor breaker, an underground circuit runs to a 2,300-volt bus in the switchgear room, which in turn feeds the main pump starters as well as a 2,300-to-460-volt transformer bank serving all the station auxiliaries. Energy for the control circuits of the motor starters and for signal lights and alarms is furnished at 230 volts through a transformer from the station auxiliary supply. A single-phase transformer connected to the 2,300-volt service ahead of the station power breaker supplies station lighting and outdoor lighting at 115/230 volts through separate low-voltage outdoor breakers. At some of the stations there are loads outside the station proper, such as fire pumps, water well pumps, and warehouse, which must be operable even when the pumping station is shut down. To carry these loads, as well as the lighting load, a 2,300-volt bus is provided on the outdoor structure, connected to the power service ahead of the station power breaker. To this outdoor 2,300-volt bus are connected the station bus breaker, the lighting transformer, a 2,300-to-460-volt transformer bank for outside auxiliaries and a 2,300-volt fire pump circuit.

With this arrangement of circuits, shown schematically in Figure 4, the station operator can clear all power circuits within the station proper by opening the 2,300-volt outdoor circuit breaker. This he can do either from within the station or at the substation. At the same time he can leave the station lights and outside auxiliaries in operation if required, since these circuits are not affected by tripping the outdoor breaker.

Figure 7. Control desk set into vaportight wire-glassed partition, through which the pump room is clearly visible

Control System

A fundamental consideration in establishing the control system was that of station attendance; it was decided at the start that:

1. In the interest of safeguarding property, each station must have attendance at all times.
2. During the tour of duty the attendant may be at any part of the station property, subject to prompt arrival at the control room upon signal.
3. In the simple booster stations the at-

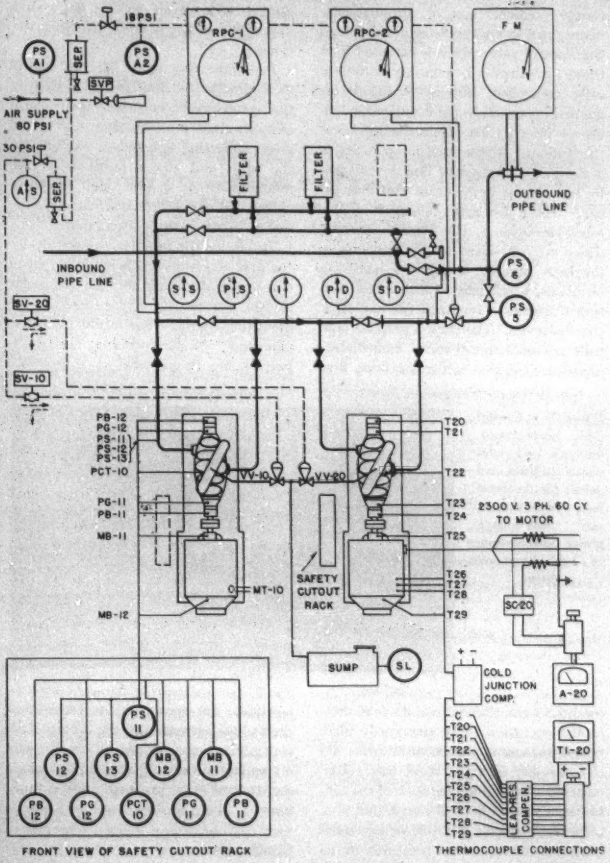

Figure 8. Schematic diagram of station control system for typical two-unit station

tendant will perform singly all operating duties incidental to starting, running, and stopping units, as required by the central dispatching office.

4. Maintenance work except of minor nature is to be handled by established maintenance personnel, progressing from station to station. In case of difficulty or failure in the operation of equipment, specialized repair personnel will be available on call to the superintendent of the division.

These operating conditions determine the following essential features of the system of control:

(*a*). Starting and normal stopping of the stations and of units within each station shall be controlled by the station attendant.

(*b*). Protective shutdown of units and stations must be instituted automatically when conditions arise that exceed predetermined limits of safe operation.

(*c*). In case of automatic protective shutdown, a signal must be given to inform the attendant that shutdown has occurred, and indication must be given of the specific protective function that caused shutdown.

(*d*). In the starting and stopping of mainline units, it is desirable to simplify the duties of the attendant by providing automatic operation in proper sequence for the valves, motor control, and pressure devices concerned. The operator, thus relieved from performing a routine of manual operations at different points in the station, can devote his attention to the over-all process and to the results obtained.

(*e*). For continuous operation of the line it is, of course, necessary to maintain pressure conditions within the limits predetermined for protective shutdown, and this should be accomplished by automatic means.

Design of Station Control

The control system developed to meet these requirements embodies the co-ordinated application of pressure, temperature, and electrical control and indicating devices.

Each pump unit normally is controlled from an individual "start–stop" push-button, the control system providing a predetermined sequence of operations. Considering a typical two-unit booster station, this control system provides automatic means for:

1. Venting the pump casings during shutdown to prevent building up of pressure within them by leakage past suction or discharge valves.

2. Permitting the starting of a unit only upon existence of a predetermined minimum suction pressure.

3. Operating in correct sequence a motor-driven suction valve and a motor-driven discharge valve for each unit.

4. Venting vapor from the pump casing and circulating liquid through the pump during starting.

5. Adjusting the station capacity to the line throughput while the station is on the line.

6. Limiting the minimum value of station suction pressure to a value safe for pump operation.

7. Limiting the maximum value of the station discharge pressure to a value safe from the standpoint of pipe-line stress.

8. Safety shutdown, sounding the station alarm and lighting an individual indicating light, in case of:

	See Figure 8 Symbol
Excessive duration of high motor starting current	*SC*-20
High motor-winding temperature (alarm and light only)	*MT*-10
Power-supply failure (alarm only—air operated)	*SV-P*
High motor-bearing temperature (front or rear bearing)	*MB*-11, *MB*-12
High pump-bearing temperature (front or rear bearing)	*PB*-11, *PB*-12
High pump-gland temperature (front or rear gland)	*PG*-11, *PG*-12
High pump-casing temperature	*PCT*-10
Low suction pressure pumps 1 and 2	*PS*-11, *PS*-21
High suction pressure pump 1 and 2	*PS*-12, *PS*-22
High station discharge pressure	*PS*-5
Low station discharge pressure	*PS*-6
Low air-supply pressure to hydraulic controllers (alarm and light only)	*PS*-A2
Low station air-supply pressure (alarm and light only)	*PS*-A1
High sump-tank level (alarm and light only)	*SL*

An ammeter (*A*-20) and ammeter switch are provided for each unit, also a common temperature indicator (*TI*-20) for both units with a selector switch for

each unit whereby the temperature indicator may be connected, per unit, to any one of:

	See Figure 8 Symbol
2 Pump-bearing thermocouples	*T*-21, *T*-25
2 Pump-gland thermocouples	*T*-22, *T*-24
1 Pump-casing thermocouple	*T*-23
2 Motor-bearing thermocouples	*T*-20, *T*-26
3 Motor-winding thermocouples	*T*-27, -28, -29

The gauge panel mounts a flowmeter (*FM*) for indicating and recording the rate of flow at or by the station, also two pressure controllers (*RPC*-1, *RPC*-2) whose function will be discussed below, and six gauges indicating pressure at the following points:

	See Figure 8 Symbol
Station suction	*SS*
Pump suction	*PS*
Interpump	*IP*
Pump discharge	*PD*
Station discharge	*SD*
Air supply to air operated vent valves	*AS*

Pump Venting

Each pump has a connection from the top of its casing through a vent valve to the station sump. The vent valve (*VV*-10, *VV*-20) is spring-opened, air-closed, the air supply being controlled by a three-way solenoid valve (*SV*-10, *SV*-20). This valve is so connected in the motor-control sequence that the vent valve is open while the pump unit is down and remains open during the starting cycle until the pump discharge valve is fully open, whereupon the solenoid valve is energized to close the vent valve. In a shutting-down cycle, when the pump discharge valve leaves its open position, the solenoid valve is de-energized to open the vent valve. At the conclusion of the shutting-down cycle both the discharge valve and the suction valve are closed, and flow through the pump-venting system ceases.

Station Pressure Control

The regulation of station pressure is accomplished by air-actuated instruments such that the station suction and discharge pressures can be automatically maintained at any predetermined values. The control valve which is actuated from these instruments is normally automatically controlled, but is equipped for manual operation in the event of air failure or interruption of electric service at the stations. All the stations operating in a continuous section of line are affected by any change in flow rate that may occur. There are many changes in flow rate throughout the entire system. These are occasioned by the existence of the large number of delivery points or terminals, which may be utilized for multiple deliveries or for single full-line capacity deliveries. The station pressure controls are so designed as to immediately adjust each station to these varying flow conditions and thereby maintain uninterrupted operation. The previously mentioned automatic shutdown features are co-ordinated with the regulating equipment, so as to permit operation of the control system over its full range, and only to prevent operation of one or two units in the station in case the pressures exceed pre-established limits.

Control Desk

Physically, the control for each station centers in a control desk in the control room, where also is situated the gauge board previously mentioned, the attendant's working desk, and a teletype operating over a circuit serving the system dispatcher's office and all pumping stations.

Red indicating lights on the control desk identify the functioning of each of the protective shutdown and alarm switches already mentioned. Amber and green indicating lights show respectively the open and closed positions of the motor-operated suction and discharge valves and of the principal manually operated valves in the station piping.

To clarify the function of each device the desk top bears a schematic layout of the principal piping for the particular station, and in this piping diagram the indicating lights, temperature indicator, ammeters, selector switches, and push-buttons are all mounted in appropriate position. An accompanying illustration shows how conveniently the control desk and gauge board in one of the stations serves as the central point for indication and control of all principal station functions.

Figure 9. Control desk, gauge board, teletype and telephone facilities, and panels for incoming line, motor starters, and low-voltage power distribution, in a typical two-unit station

Conclusion

As evident from this discussion, the electrification of the Plantation system was designed to meet the practical requirements of products-line operation. That it adequately serves these needs is indicated by operating experience with the system to date, which has verified all fundamental features of its design.

Protection of Pilot-Wire Circuits

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THIS paper reviews the problem of protecting pilot-wire circuits, briefly discusses the sources of disturbing voltages, describes two types of neutralizing transformers, and illustrates how they are used to distribute the disturbing voltage most favorably throughout the pilot-wire circuit. The recent increase in use of high-speed pilot-wire relays for the protection of important power circuits has accentuated the need of better understanding of the pilot-wire protection problem. Therefore, a review of this general subject and a description of a new type of neutralizing transformer with mathematical formulas to determine its effectiveness, is considered timely.

Three principal objectives to be attained when applying pilot-wire protective apparatus are:

1. To assure correct operation of the protective relays or other apparatus at all times.
2. To protect operating personnel.
3. To protect the apparatus.

Pilot circuits for protective relaying must be operative at all times, especially at times of system disturbances. Thus, simple protective gaps which provide adequate protection for many other pilot services cannot be used to protect against voltages induced by the power-system currents, as this would render the circuit inoperative when most needed. Certain supervisory control and other functions are also required to be operative during power-system faults, and this discussion applies equally well to pilot circuits for these purposes. The principles and methods will also be found useful in applying protection to those telemetering and supervisory control circuits which are not required to be operative during power-system faults.

A pilot circuit may be exposed to disturbing voltages of several sorts, which will be discussed subsequently. Briefly, these are:

(*a*). Lightning and other surges.

(*b*). Induction from power lines.

(*c*). Elevation of station ground potential.

(*d*). Direct crosses with power circuits.

If these voltages are not to disrupt the proper operation of the circuit, they must be disposed of by some combination of the following measures.

(*a*). By insulating the circuit to stand them.

(*b*). By distributing them through design of the circuit impedances and grounds.

(*c*). By the use of gaps or arresters to prevent surge voltages from reaching excessive values.

(*d*). By drainage—dissipating the disturbing voltages as impedance drops in the circuits.

(*e*). By shielding the wires or so locating them that the disturbing voltages are lessened.

(*f*). By using insulating transformers or neutralizing transformers to take up longitudinal voltages as will be explained.

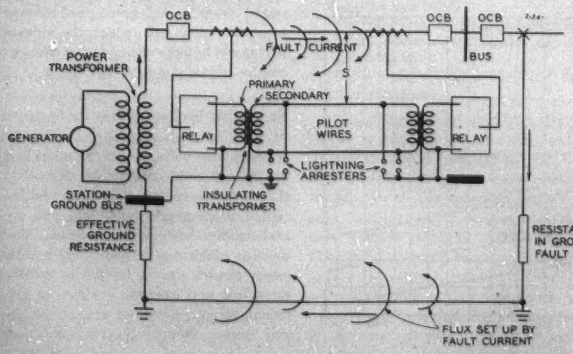
In many cases no specific protective measures are required. This is frequently the case when rubber-lead-covered control cable is used in relatively unexposed locations. However, a consideration of the magnitudes of disturbing voltages is worth-while in any case, to insure that the pilot circuit, through its insulation, arrangement, and protective features, provides adequately for the voltages to be encountered.

Pilot-wire circuits that are totally enclosed in a frequently grounded sheath are inherently provided with a high degree of protection against lightning. Circuits of this kind, that are not exposed to induction from transmission lines and that enter stations in which only small ground potentials can occur, require no special protective measures. The auxiliary equipment that will be discussed is needed only when calculation or measurements indicate voltages in excess of the normal insulation strength.

The general problem is very much as follows: Assume that lightning strikes the power line and causes a phase-to-ground fault at the far end of the line section that is protected with pilot-wire relays. Assume also that the pilot circuit is exposed to the effects of the same lightning stroke. Arresters on the pilot wires must operate to protect the relays and associated equipment. However, the arresters must immediately seal off and interrupt any power follow, so as to make the pilot circuit operable. The seal-off voltage of the arresters must be above the maximum voltage that can be impressed on them by induction in the pilot wires or by a combination of a rise in ground potential and induction which can be caused by the flow of transmission-line fault currents. If the arresters should fail to seal off, they would effectively short-circuit the pilot wires and block operation of the protective relays. Similarly, provision must be made to guard against the accidental operation of pilot-wire relays which may be caused by unsymmetrical operation of the arresters. This may be accomplished, for example, by connecting a low-voltage protector tube between the pilot wires, as shown in Figure 4 and by distributing fundamental frequency-disturbing voltages so

Figure 1. Schematic diagram of faulted transmission line and pilot-wire relay circuit

S=Separation between pilot wire and power line



Paper 42-136, recommended by the AIEE committee on protective devices for presentation at the AIEE summer convention, Chicago, Ill., June 22-26, 1942. Manuscript submitted April 9, 1942; made available for printing May 25, 1942.

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The authors acknowledge the assistance of J. E. Barkle in preparing many of the potential-gradient diagrams.

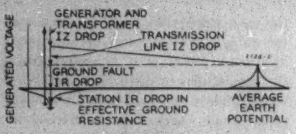

GENERATED VOLTAGE
GENERATOR AND TRANSFORMER IZ DROP
TRANSMISSION LINE IZ DROP
GROUND FAULT IR DROP
STATION IR DROP IN EFFECTIVE GROUND RESISTANCE
AVERAGE EARTH POTENTIAL

Figure 2. Distribution of voltages in transmission-line and ground circuits

IX_L component of line drop equals maximum possible voltage that can be induced in pilot wires

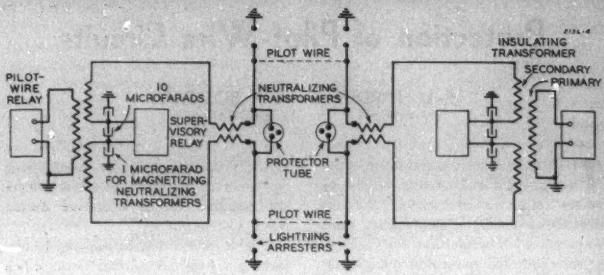


Figure 4. Protective apparatus

as to avoid operating the lightning arresters.

To aid in visualizing the manner in which these disturbing voltages may be impressed on the pilot-wire circuits by transmission line faults, consider the circuit that is illustrated in Figure 1. Inasmuch as these disturbances are most severe when one phase of the transmission line is grounded, only a single-phase system is drawn. As shown in Figure 1, assume that the faulted power system consists of a single-phase generator, a grounded transformer, a section of line, and equivalent ground-fault resistance. The pilot-wire circuit is spaced from the power-line conductor, a distance of S feet.

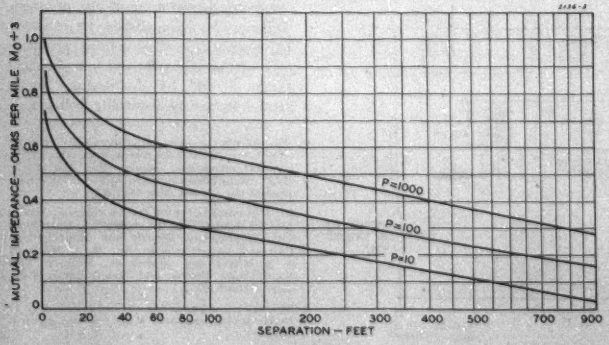
When the ground fault occurs, current will flow out through the transmission line and return through the ground. The generated voltage is used up in a series of voltage drops in the generator and transformer, line, ground-fault resistance, and the effective resistance that can be measured between the station ground bus and true ground. This resistance, indicated in Figures 1 and 2, varies from a fraction of an ohm in well-grounded stations to several ohms in stations that are not so well grounded. The value may be high or low, depending upon the earth resistivity in that vicinity. Ground potential rises of 1,000 to 3,000 volts are not uncommon, while values up to 15,000 volts are sometimes encountered.

The manner in which voltage is induced in the pilot-wire circuit is indicated in Figure 1. Fields of flux are set up by the flow of current in the transmission line and in the earth return. These fluxes link both pilot wires and induce voltages along the length of the exposed portion of the pilot-wire circuit in proportion to the magnitude of the flux linkages. If a twisted or spiraled pair of wires is used for the pilot circuit, no appreciable voltage difference will appear between the pilot wires. This is important, for the voltage difference that appears between the pilot wires must be limited to avoid operating the protective relay, or associated apparatus that is connected to the pilot circuit. Because of this, only longitudinally induced voltages, which are equal and in the same direction in both wires, will be discussed.

It will be noted that the flux which links the pilot wires from the ground current is 180 degrees out of phase with respect to that set up by the transmission-line current. Consequently, these two fields tend to cancel, or it may be said that the ground current tends to "shield" the pilot wires from induction. This effect becomes quite appreciable when ground wires carry a large portion of the ground-fault current.[1]

Figure 3 illustrates how the mutual impedance between the transmission line and pilot wires varies with the separation between the two circuits. Three different curves are drawn to illustrate how this quantity is affected by extreme variations in the resistance of the earth-return circuit or how the earth currents "shield" the pilot circuit from induction. When the earth resistivity is high, current returns deep in the ground and produces less shielding. The ground-fault current multiplied by the proper mutual impedance equals the magnitude of voltage that will be induced in the pilot-wire circuit. Note that this quantity can never exceed the magnitude of the transmission-line reactance drop. A voltage equal to that magnitude can be obtained only when the transmission line and pilot wires occupy the same space or have 100 per cent coupling. It should also be remembered that ground wires and return circuits that are provided by cable sheaths all tend to reduce the magnitude of the induced voltage. In general, the shielding that is obtained from a full-sized, lead-covered telephone cable will reduce the voltage that would be induced in an open-wire circuit by approximately 50 per cent.[1]

Figure 3. Approximate variation in mutual impedance between transmission circuit and pilot wires



Protective Measures

Disturbing voltages can be impressed on the pilot-wire circuits by lightning, electrostatic and electromagnetic induction, station ground potentials, and actual contact with power circuits. The damage which results from crosses with power circuits can be limited by solidly grounding and isolating portions of the circuit through action of arrester blocks and fuses. Frequently this will cause

relay operations that cannot be prevented. Voltages impressed on the circuit by lightning, induction, and ground potentials can be dissipated, distributed, or isolated with insulation in a manner that will not cause relay operation. This is accomplished by use of lightning arresters (which must be chosen so that they cannot be operated by system disturbances), by draining appreciable amounts of currents from the circuit through mid-tapped transformers or similar balanced impedances, by altering the natural distribution of voltage stresses, with neutralizing transformers or grounding impedances, and by insulating the apparatus or isolating it with insulating transformers so that it will withstand the applied voltage.

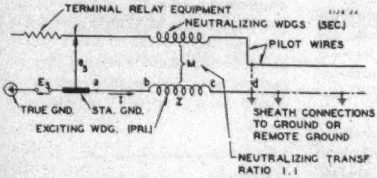


Figure 5a. Three-winding neutralizing transformer neutralizing station ground potential

I = Neutralizing - transformer exciting current
r = Resistance of exciting-winding connections a-b and c-d
Z = Self-impedance of exciting winding
M = Mutual impedance between exciting winding and secondary windings
e_s = Remnant or unneutralized voltage which appears between relays and station ground
Z_p = Primary leakage impedance = $Z - M$

$$e_s = E_s \frac{Z_p + r}{Z + r} \qquad (1)$$

Insulating transformers have long been used to insulate the terminal equipment from disturbing voltages in pilot-wire circuits. They are also used to keep station ground potentials off the pilot wires. Insulation built directly into the relay can be used in a similar manner. This action is illustrated with typical graphical solutions in the latter part of this paper. The effects of electrostatic and electromagnetic induction can be counteracted directly in the pilot wires by current drainage, as by grounding the mid-points of the insulating transformers at both ends of the line. When this is done, it is necessary to consider thermal capacities of the equipment and inequalities in voltage drop in the individual pilot wires as any lack of symmetry in the circuit tends to insert an extraneous (unbalanced) voltage in the pilot loop and may affect the associated relay operation. Neutralizing transformers are used in circuits of this kind to reduce the circulating current to an absolute minimum and to provide a control means that can be used in d-c circuits.

To study the action of neutralizing transformers and determine the distribution of the disturbing voltages, pilot-wire equipment should be classified into groups at different potentials somewhat as follows:

1. Terminal equipment at station ground potential. In Figure 1 this includes the current transformers and relay parts up to and including the primary of the insulating transformer.

2. Terminal equipment on the station side of a neutralizing transformer. As neutralization is not perfect, this equipment operates at the remnant or unneutralized voltage to ground. In Figure 4 this includes the supervisory relay, secondary winding of the insulating transformer, and the capacitor between the two center taps of the insulating transformer.

3. The incoming pilot wires, any equipment connected thereto, and their potential with respect to ground.

4. The cable sheath, usually at true ground potential if insulated, or at station ground if connected thereto.

5. Other wires in the cables, and their potential to ground.

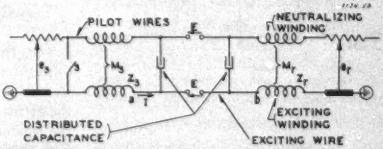


Figure 5b. Three-winding neutralizing transformer neutralizing longitudinally induced voltage

Z = Impedance of ground return circuit, a to b
E = Longitudinal voltage induced equally in pilot and neutralizing wires
m = Mutual impedance between exciting wire-ground return circuits, from a to b
$Z_{sp} = Z_s - M_s$, $Z_{rp} = Z_r - M_r$, primary leakage impedances
Total remnant voltage:

$$e_s - e_r = E \frac{Z_{sp} + Z_{rp} + z - m}{Z_s + Z_r - z} \qquad (2)$$

Some of these items span from one potential to the other. The neutralizing transformers span from (3) to (2); that is, from the pilot wires to the remnant voltage point. The grounding capacitors span from (2) to (1); that is, from remnant voltage point to station ground. The insulating transformers span from (2) to (1).

Cable sheaths, if not connected to station ground, may usually be considered as at true ground throughout their lengths. They are usually grounded by leakage if not intentionally. Aerial cables with sheaths purposely insulated require a study of the various capacitive impedances, between wires and sheath, and sheath to ground, to determine the voltage with which their insulation is stressed. If a sheath is grounded along the line and also grounded to station ground, a heavy current will flow over it when there is a rise of station ground potential. The steepness of gradient along the cable sheath from station ground to true ground will depend on the resistance of the "pole grounds." Possible danger of burning the sheath should be checked, especially if the cable is buried under the power line so that it may carry a considerable part of the return fault current.

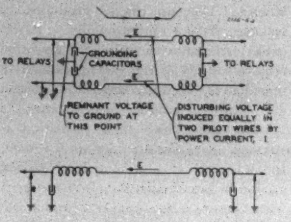
With given voltages, impressed on the pilot-wire circuit by longitudinal induction or a rise in station ground potential, the determination of voltage distribution as indicated above is a problem in conventional circuit theory. After determining each potential with respect to any convenient reference, such as true ground, the potential differences are obtained for verifying or designing the insulation coordination. Graphic examples of this are given after operation of the neutralizing transformers is explained.

Three-Winding* Neutralizing Transformer

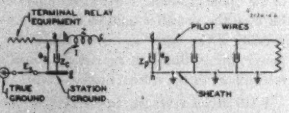
When used to protect against a difference in ground potential, the exciting winding of the three-winding neutralizing transformer is connected between true ground (remote pole ground) and the station ground as shown in Figure 5a. The pilot wires are connected in series with the secondary windings of the neutralizing transformer and thereby have a voltage almost equal and opposite to the station ground-potential rise impressed directly on them. Thus, with the pilot wires at true ground potential (sheath potential usually), the terminal relay equipment will be held close to station ground potential.

The connection from the exciting wind-

* Three winding is used to distinguish the type having a separate exciting winding. There may be any number of secondaries. Usually, there are two, through which a pair of pilot wires is carried.


TO RELAYS
GROUNDING CAPACITORS
TO RELAYS
REMNANT VOLTAGE TO GROUND AT THIS POINT
DISTURBING VOLTAGE INDUCED EQUALLY IN TWO PILOT WIRES BY POWER CURRENT I

(a) Actual and single-line representation of circuit with neutralizing transformers



(b) Neutralizing station ground potential

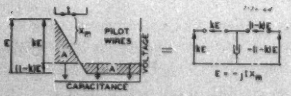
r = Resistance of pilot wires in parallel from a to b and c to d

Z_p = Impedance of pilot wires to ground (usually sheath) looking into terminal d-n, including distributed capacity and terminating impedances

Z_c = Parallel impedance of grounding capacitors from a to g

(c) General case—neutralizing station ground potential and longitudinal induction

E = Total longitudinal induced voltage



(d) Equivalent circuit for pilot wires having induced voltage and distributed and lumped capacitance

Figure 6. Two-winding neutralizing transformer

ing to ground may be a wire carried out a few hundred feet to a pole ground. Or the cable sheath may be insulated for the last few hundred feet into the station and the exciting winding of the neutralizing transformer connected between it and station ground.

Assuming the pilot wires to be at true ground potential as indicated schematically by the dotted connection at d, Figure 5a, the remnant or unneutralized voltages between the terminal relay equipment and station ground can be expressed as a function of the station ground-potential rise, E_s, and the circuit constants shown. The voltage e_n is the difference between the voltage drops from f to d, and a to d, due to I. Thus:

$$e_n = E_s \frac{Z_p + r}{Z + r} \qquad (1)$$

Commercial designs have been described[2] having 0.35 ampere exciting current with 4,000 volts applied to the primary winding. This results in an impedance Z = 4,000/0.35 or 11,400 ohms. The primary leakage impedance, Z_p, has been held to a value such that with a disturbing voltage, E_s, of 4,000 volts, the remnant voltage e_n is 70 volts for r = 0, and 81 volts for r = 35 ohms. (r is the resistance of the exciting winding connections.)

The three-winding type of neutralizing transformer has also been used for neutralizing induced voltages.[3] In applications of this kind an exciting wire is run the full length of the pilot wires and has induced in it the same voltage as the pilot wires. However, the cost of the exciting pilot wire, which must be held to a low value of resistance, usually eliminates this scheme from consideration.

Two-Winding Neutralizing Transformer

The two-winding neutralizing transformer (or longitudinal choke) is a new form of neutralizing transformer in which the exciting current is conducted through the windings that are connected in series with the pilot wires and otherwise operates in the same manner as the three-winding neutralizing transformer. This design was introduced in 1935. The first application was for protection of extensive pilot wires along an a-c railway electrification.

The two-winding neutralizing transformer is designed to protect pilot wires and their terminal equipment from station ground potentials and longitudinally induced voltages. Its self-exciting feature is particularly valuable for applications which involve longitudinal induction, as it eliminates the need of a third pilot wire. Furthermore the device is more effective than the three-winding transformer, when used to counteract induced voltages, as the magnetizing currents flowing through the pilot circuit actually aid the neutralizing action.

By providing grounding capacitors as shown in Figure 6a, a complete excitation path is secured over the pilot wires. The resulting circuit which includes the induced voltage and the neutralizing transformers is termed a "self-exciting neutralizing-transformer circuit," since the exciting current is carried over the pilot wires which are also used for relaying.

The two windings of the neutralizing transformer are wound in the same direction on the core, so that currents which flow in the same direction in the pilot wires encounter exciting impedance, whereas relay loop currents, in opposite directions in the two pilot wires, encounter only the leakage impedance. The exciting impedance of such neutralizing transformers can readily be made as high as 100,000 ohms at 60 cycles with only 160 ohms added to the pilot-wire loop resistance. One-microfarad grounding capacitors, connected one from each wire to ground, have a parallel impedance of

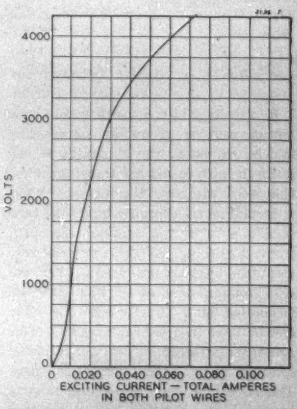


Figure 7. Saturation curve of typical two-winding neutralizing transformer (longitudinal choke coil)

1,325 ohms at 60 cycles and limit the remnant voltage to about 1.3 per cent of one half of the induced voltage. This assumes balanced conditions in which one half of the voltage is impressed across neutralizing transformers at each end of the pilot wires.

Station Ground Potential

The theory of the two-winding type of neutralizing transformer, as used for neutralization of station ground potentials, may be understood from a consideration of Figure 6. The two pilot wires are considered paralleled, so that the parallel impedances are used. The remnant voltage, e_n, of the terminal relay equipment from station ground is given by

$$e_n = -IZ_c = -E_s \frac{Z_c}{Z_c + Z + Z_p} \qquad (2)$$

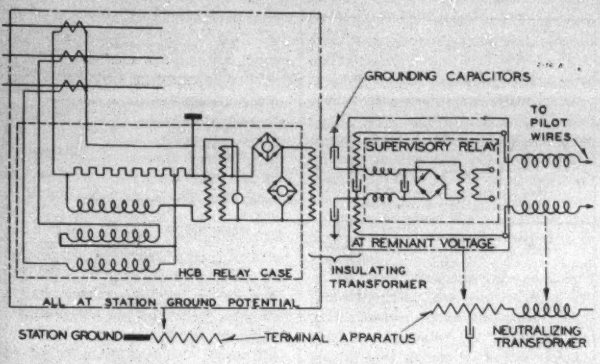


Figure 8. Actual connections

Arrows show parts included in each symbol of the potential-gradient diagrams

The voltage from the pilot wires to the cable sheath is

$$e_p = -IZ_p = -E_s \frac{Z_p}{Z_c + Z + Z_p} \qquad (3)$$

In practice, the neutralizing-transformer exciting impedance Z is very large, compared with the other impedances in the circuit. Therefore, the neutralizing transformer has impressed on it approximately the full disturbing voltage, E_s. The corresponding exciting current can be determined by reference to its saturation curve, see Figure 7. The remnant voltage, e_p, is then numerically the product of the exciting current, I, and the impedance, Z_c of the grounding capacitors (see equation 2). Similarly, the voltage from pilot wires to sheath is the exciting current I multiplied by Z_p, defined in Figure 6b (see equation 3). If the distributed capacitance is small, the voltage drop from the pilot wires to the sheath may be high. This can be reduced by adding lumped capacitance ground at d or terminating impedance to ground at the other end of the line.

Figure 7 shows the excitation characteristics of a commercial design of a two-winding neutralizing transformer. At 3,000 volts the exciting current is 30 mils (15 mils in each winding), or the exciting impedance, Z is 100,000 ohms. At 4,000 volts the exciting current is 0.062 ampere. The impedance inserted in the relay loop circuit by this design is $160+j\,130$ ohms, per transformer, at 60-cycle frequency.

Longitudinal Induction

The theory of the two-winding neutralizing transformer, used for protection against longitudinally induced voltages, is given in the appendix. This treatment covers the general case in which both longitudinal induction and station ground-potentials are present. Remnant voltages for the simpler case of longitudinal induction only are obtained using the same equations with the station ground potentials set equal to zero.

The potential distribution is influenced by the relative values of terminating impedances to ground and distributed impedances to ground as well as the locations and amounts of induced voltages. These factors are taken into account in the exact theoretical treatment of the appendix. The important case in which a station ground-potential rise and longitudinal induction are both caused by the same primary fault current is fully developed, the voltage distribution being expressed by equations 5a to 9a of the appendix.

Potential Distribution for Typical Conditions With and Without Neutralizing Transformers

A reasonably accurate conception of the potentials existing in various parts of a pilot-wire circuit that is exposed to station ground potential or longitudinal induced voltage may be obtained from the typical diagrams in Figure 9. The potentials shown are based on 2,000 volts station ground potential or 4,000 volts longitudinal induction as indicated, but can be ratioed for other values of disturbing voltage. Various parts of the circuit are represented by symbols drawn in position to show the voltages to ground at which those parts operate under the abnormal conditions. In this discussion, operating voltages between wires are taken as zero, and the two wires are represented as one for determining voltages to ground. The operating voltages are usually negligible in comparison but can be superposed if appreciable.

Figure 8 illustrates which parts of a typical pilot-wire relay are included in terminal apparatus at "station ground potential," and which part operates at the "remnant voltage" to ground. The insulating transformer presents negligible impedance to pilot-wire currents in the same direction (two-winding neutralizing-transformer exciting currents) which flow to ground. It may, therefore, be considered as operating at the remnant voltage, although physically it is in the circuit between the terminating capacitances and the neutralizing transformer.

Parts (a) to (d) of Figure 9 show the distribution of 2,000 volts station ground potentials. Part (a) is without neutralizing transformers; it illustrates the distribution of voltage that is obtained when an insulating transformer is connected between the relay and pilot wires. Note that the relay is held at station ground potential, and the entire voltage difference is impressed across the transformer insulation. If a supervisory relay were connected directly to the pilot wires, with its base connected to station ground, its insulation would be stressed with the full 2,000 volts rise in ground potential.

If the cable sheath is tied to station ground, the rise in potential of the pilot wires depends on the relative lengths of pilot wires affected by sheath sections at true ground and higher potentials. For example, if one tenth of the length of cable sheath is elevated 2,000 volts and nine tenths is at true ground, the wires will rise to ten per cent of 2,000 volts, or 200 volts above true ground. If only one per cent of the sheath is elevated, the potential rise will be a corresponding proportion of the rise in the short length of sheath. A wire-to-sheath potential approaching the full station ground potential must then be provided for in the cable insulation. This illustrates that voltage stress on the cable can be reduced by insulating the cable sheath from station ground.

The use of two-winding neutralizing transformers is illustrated in parts (b) and (c). This transformer holds the relay parts that are metallically connected to the pilot wires at station ground potential, except for the small remnant voltage, caused by the neutralizing transformer exciting current passing through the capacitance to ground. These remnant voltages are usually under 100 volts. The effects of predominant and negligible pilot-wire distributed capacity are also shown in (b) and (c). The rise in pilot-wire potential indicated in (c), can be reduced by connecting small fixed capaci-

tors between the pilot wires and ground. The circuit then becomes equivalent to that shown in (b). In each case, the effect of connecting the sheath to station ground is shown. The resulting condition is tolerable, if the cable has ample insulation, and its sheath has ample current-carrying capacity. However, the sheath must be insulated from station ground if the cable is not insulated to stand 50 per cent to 100 per cent of the ground potential rise, with a suitable margin.

As shown in part (d), the three-winding neutralizing transformer produces a potential distribution under conditions of station ground voltage rise, substantially the same as for the two-winding neutralizing transformer with predominant distributed capacity.

The distribution of potentials resulting from 4,000 volts of longitudinal induction is illustrated in parts (e), (f), (g), and (h), taking into account the following variables:

With and without neutralizing transformers (two-winding type).

Pilot-wire capacitance predominant or negligible.

Different exposure conditions.

Parts (e) and (f) show that with predominant distributed capacity, introduction of neutralizing transformers leaves the pilot-wire voltages unchanged and simply lowers the potential of any relay equipment metallically joined to the pilot wires, to substantially station ground potential.

The natural distribution of pilot-wire potential determined by distributed capacitance, as explained in the appendix, can be modified by terminating capacitances to ground indicated in Figure 9(c) and (g). The distributions are shown, in part (g), for the case of distributed capacitance negligible compared with these terminating capacitors, and in part (c) for the case of distributed capacitance predominant. Other cases fall in between. The unbalanced voltage distribution which results from heavy induction near one end, when distributed capacitance is predominant, part (c), can be equalized by the addition of terminating capacitances.

As shown in parts (f) and (h), the neutralizing transformers operate to hold the relay equipment substantially at station ground potential except for the remnant voltage. Part (h) of Figure 9 also illustrates the use of a number of neutralizing transformers, connected at intervals in the pilot-wire circuit. This expedient is used to reduce voltages on the cable itself, as neutralizing transformers at the

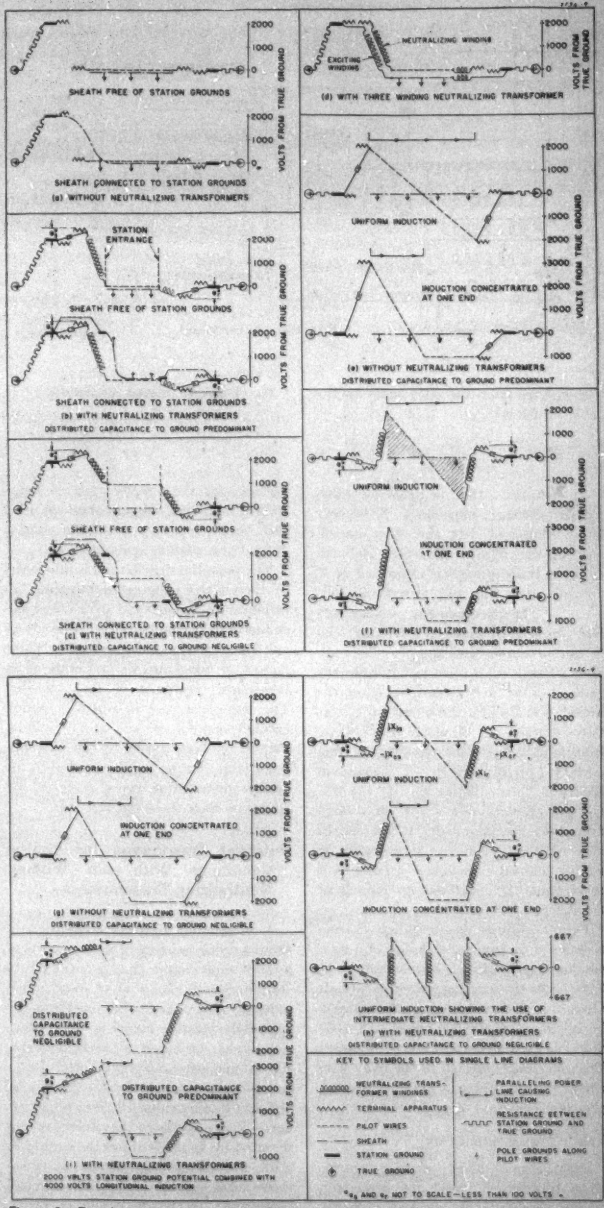

SHEATH FREE OF STATION GROUNDS
SHEATH CONNECTED TO STATION GROUNDS
(a) WITHOUT NEUTRALIZING TRANSFORMERS
NEUTRALIZING WINDING
EXCITING WINDING
(d) WITH THREE WINDING NEUTRALIZING TRANSFORMER
STATION ENTRANCE
SHEATH FREE OF STATION GROUNDS
SHEATH CONNECTED TO STATION GROUNDS
(b) WITH NEUTRALIZING TRANSFORMERS
DISTRIBUTED CAPACITANCE TO GROUND PREDOMINANT
UNIFORM INDUCTION
INDUCTION CONCENTRATED AT ONE END
(e) WITHOUT NEUTRALIZING TRANSFORMERS
DISTRIBUTED CAPACITANCE TO GROUND PREDOMINANT
SHEATH FREE OF STATION GROUNDS
SHEATH CONNECTED TO STATION GROUNDS
(c) WITH NEUTRALIZING TRANSFORMERS
DISTRIBUTED CAPACITANCE TO GROUND NEGLIGIBLE
(f) WITH NEUTRALIZING TRANSFORMERS
DISTRIBUTED CAPACITANCE TO GROUND PREDOMINANT
VOLTS FROM TRUE GROUND
UNIFORM INDUCTION
INDUCTION CONCENTRATED AT ONE END
(g) WITHOUT NEUTRALIZING TRANSFORMERS
DISTRIBUTED CAPACITANCE TO GROUND NEGLIGIBLE
DISTRIBUTED CAPACITANCE TO GROUND NEGLIGIBLE
DISTRIBUTED CAPACITANCE TO GROUND PREDOMINANT
(i) WITH NEUTRALIZING TRANSFORMERS
2000 VOLTS STATION GROUND POTENTIAL COMBINED WITH 4000 VOLTS LONGITUDINAL INDUCTION
UNIFORM INDUCTION SHOWING THE USE OF INTERMEDIATE NEUTRALIZING TRANSFORMERS
(h) WITH NEUTRALIZING TRANSFORMERS
DISTRIBUTED CAPACITANCE TO GROUND NEGLIGIBLE
KEY TO SYMBOLS USED IN SINGLE LINE DIAGRAMS
NEUTRALIZING TRANSFORMER WINDINGS
TERMINAL APPARATUS
PILOT WIRES
SHEATH
STATION GROUND
TRUE GROUND
PARALLELING POWER LINE CAUSING INDUCTION
RESISTANCE BETWEEN STATION GROUND AND TRUE GROUND
POLE GROUNDS ALONG PILOT WIRES
e_0 AND e_T NOT TO SCALE—LESS THAN 100 VOLTS

Figure 9. Distribution of wire-to-ground voltages caused by station ground potential and longitudinal induction

(a) to (d)—2,000 volts station ground potential

(e) to (h)—4,000 volts longitudinal induction

(i)—Combination of 2,000 volts station ground potential and 4,000 volts longitudinal induction

terminals provide adequate protection for the relay equipment.

Part (i) illustrates the potential gradient that is obtained when a combination of station ground potential and longitudinal induction exists. As one of these voltages is produced by resistance coupling and the other by mutual reactance coupling from the same current, the two are 90 degrees out of phase with each other. (The voltage produced by mutual coupling is ahead, if the reference directions are used as indicated in Figure 6, and the pilot wires are more closely coupled to a power phase wire than to the ground return.) As a result the voltage along the pilot wires varies not only in magnitude but also in phase position. Figure 9(i), shows the voltage magnitude to ground, of the principal parts of the circuit, but does not indicate the magnitude of voltage across the neutralizing transformers. The vectorial shift of the voltages along the pilot wires is illustrated in Figure 10.

The distribution of voltages that are imposed on pilot-wire circuits and their terminal equipments, by induction and station ground potentials, can be determined by use of the equations and diagrams presented herein. It will be noted that in many instances this can readily be accomplished by first determining the distribution of induced voltages, per Figure 6d, and then adding the rise in ground potential at right angles to it at the correct location in the circuit. The maximum stress on the pilot-wire insulation can be determined in this manner. If relay equipment is connected directly to the pilot-wire circuit, its insulation (and operating characteristics) must be able to withstand such a voltage, or neutralizing transformers must be installed to dissipate it and reduce the voltage stress at the relay to meet operating limitations. After the voltage distribution has been determined, as mentioned above, the effect of neutralizing transformers, or the use of grounding impedances, or of insulating transformers can be determined by simply subtracting the impedance drops from the voltages that are impressed on the circuit.

In general, all parallel wires that enter a cable at a given point should be protected in a similar manner to make certain that all wires within the cable are held at the same potential. A circuit of this kind should be studied, and the necessary protective measures must be taken to avoid the transfer of disturbing voltages from one set of wires to the other.

The paper has reviewed the problem of protecting pilot-wire circuits with emphasis on high-speed relay requirements and has presented mathematical and graphic aids to help the reader visualize it. It has also presented a mathematical analysis of a new tool, the two-winding neutralizing transformer, that is well suited to use in dissipating disturbing voltages that are frequently impressed on pilot-wire circuits. Use of this "tool" and the methods of analysis described should be of value to the users of pilot-wire circuits in avoiding difficulties that have been previously overlooked. The important points to be checked are the adequacy of insulation provided at different points in the circuit, and the voltage that is impressed on the lightning arresters. This latter point is of primary importance on leased circuits that are used with high-speed protective relays. The voltage distribution must be such that lightning protection is never operated by power-system disturbances.

Appendix. General Case of Longitudinal Induction and Ground Potential

In the general case where both station ground potentials and longitudinal induced voltages are present, the voltage distribution can be determined in the following manner: First determine the distribution of the induced voltage in the pilot wires to obtain the value k; this is done with the terminal equipment disconnected. Then complete the circuit to calculate the distribution of voltages in the entire circuit as will be explained.

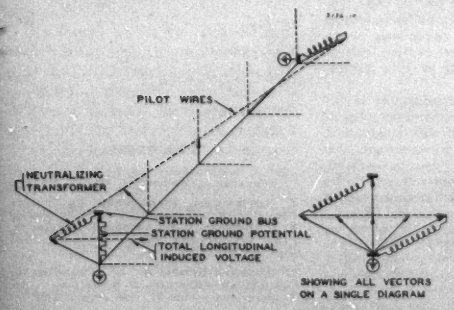


Figure 10. Vector voltage distribution along pilot wire exposed to both station ground potential and longitudinal induction

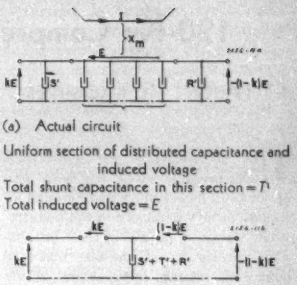


Figure 11. Potential gradient for induction in part of a section

$$k = \frac{2R' + T'}{2(R' + T' + S')}$$

Z_{cp} = Impedance corresponding to $S' + T' + R'$
All capacitances in microfarads

As shown in Figure 6d, the pilot-wire circuit can usually be replaced by a T section composed of two parts of the induced voltage, kE and $(1-k)E$, and the total shunt capacitive impedance of the two wires to ground, Z_{cp}. This assumes that voltage drops in the series impedance of the pilot wires, caused by the shunt capacitive current, are negligible. The value of k can be determined by considering the voltage distribution in the pilot wires with the neutralizing transformers and terminal equipment disconnected. If shunt impedances are all capacitive, either distributed or lumped, the voltage distribution diagram can be constructed as shown. The positive and negative areas A are made equal, since they are proportional to the charging currents entering and leaving the pilot wires, which must be equal. This is most easily visualized by referring to Figure 6d. Note that the abscissa is capacitance, rather than distance to allow for cable or open wire, and lumped capacitance effects. Thus the potential distribution diagram can be readily drawn from the known capacitances and induced voltages by making the areas equal.

One of the most common cases is shown in Figure 11. Uniform induction, of total voltage E, occurs over a section having uniformly distributed capacitance, totaling T' microfarads. The sum of remaining distributed capacitance plus lumped capacitance at one end is S' and at the other end, R'. For this case

$$k = \frac{2R' + T'}{2(R' + T' + S')} \qquad (4)$$

After the potential distribution in the pilot wire above has been determined, that is, the value of k fixed, the equivalent diagram can be connected to the terminal equipment as in Figure 6c. A vector solution of the resulting two-mesh network gives the various voltages and exciting currents.

120-Kv Compression-Type Cable

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THE oil-filled type of high-voltage paper-insulated cable has been used on all extra high-voltage underground installations now in service in this country. While the major portion of these installations operates at oil pressures under 30 pounds per square inch, several of the shorter ones utilize oil pressures up to 200 pounds per square inch ("oilostatic" type). Although an alternate system[1] in which a high gas pressure is applied externally to the lead sheath has been in commercial service abroad since 1932, it was not until recently that this type of cable, known as compression cable, received serious study here. In 1939 the Detroit Edison Company found that a system employing a welded steel pipe line offered a number of advantages over the conventional duct installation under the conditions existing over the route of a projected 120-kv underground circuit. For this reason the companies with which the authors are associated initiated an intensive laboratory and field investigation of the technical characteristics of several systems employing a steel pipe. The present paper describes some of the more interesting results of the technical investigation on the compression cable system.

Essentially the compression-cable system comprises a cable that is in most respects an ordinary solid-type cable encased in a pressure chamber in which a gas pressure of approximately 200 pounds per square inch is applied externally to the lead sheath. In any high stress design it is necessary to eliminate entirely or nullify effectively the two important inherent defects of ordinary solid-type cable:

1. The expansion and contraction of the impregnating compound with the load cycle must be provided for.

2. The small but inevitable gas occlusions within the insulation must be rendered innocuous.

In the low-pressure oil-filled cable the first requirement is taken care of by incorporating an oil-flow channel or channels within the cable and by locating along the route reservoirs having expansible cells and an external gas supply to maintain positive pressure. The second prerequisite is met by employing a design which allows more complete degassing of the oil and saturation of the paper than obtained in ordinary solid-type cable. Several investigators have patented designs in which impermeable expansible members and the associated gas supply are incorporated in the conductor or sheath of the cable itself. Because of economic considerations none of these latter designs has attained commercial recognition. In the compression cable system the cable is made noncircular so that the lead sheath by change of shape may serve as an impermeable expansible member, the action of which is made reversible by external gas pressure. Thus the cable becomes self-compensating in that on increasing load the volumetric increase is accommodated by an increase in the cross-sectional area, while on decreasing load the external gas pressure causes the reverse action to take place, thereby preventing void formation as a result of load changes.

In actual practice the compression cable is made oval in cross section so that the shape is free to change in such a direction as to alter the minor axis at the expense of the major axis and hence alter the cross-sectional area without necessitating any large change in the periphery of the cable. A thin metal binder tape with paper tape over and under it is applied over the lead sheath in order to insure uniform diaphragm action along the sheath. The external gas pressure is secured by placing the cable in a welded steel pipe line filled with nitrogen gas under pressure. By actual field and laboratory experience it has been found that a gas pressure of about 200 pounds per square inch is adequate to maintain a positive internal oil pressure sufficiently high to prevent ionization in those voids

Paper 42-133, recommended by the AIEE committee on power transmission and distribution for presentation at the AIEE summer convention, Chicago, Ill., June 22-26, 1942. Manuscript submitted April 11, 1942; made available for printing May 20, 1942.

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The authors are indebted to many of their engineering associates who have contributed to this work. They wish especially to thank S. M. Dean, W. S. Brown, F. G. Cox, R. C. Fellows, H. C. Frank, H. G. Hall, E. Johansson, L. Meyerhoff, E. Richman, C. B. Sharp, and G. J. Shurts.

These are

$$I_s = \frac{-E_r Z_{cp} + Z_{cp}(1-k)E + (Z_{cr}+Z_r+Z_{cp})(kE+E_s)}{(Z_{cs}+Z_s+Z_{cp})(Z_{cr}+Z_{cp}+Z_r)-Z_{cp}^2} \quad (5)$$

$$e_s = Z_{cs} I_s \quad (6)$$

$$e_r = e_s - E - E_s + E_r \quad (7)$$

$$E_{sp} = -E_s + I_s(Z_s + Z_{cs}) \quad (8)$$

$$E_{rp} = E_{sp} - E \quad (9)$$

E_r and E_s = station ground potentials at r and s

E = voltage induced in the pilot wires

Frequently, the shunt capacitance to ground of the pilot wire will be so large that the potential distribution of the pilot wires will be relatively unaffected by the connection of the neutralizing transformers and terminating capacitors, Z_{cs} and Z_{cr}. Test of this condition is whether the neutralizing transformer impedance (approximately 100,000 ohms for a commercial design) is large compared with the capacitive reactance to ground (sheath) of the pilot wires. In this case corresponding to $Z_{cp}=0$, the disturbing voltages can be taken as E_s+kE at the "s" end and $(1-k)E$ at the "r" end. The voltages e_s and e_r can then be determined by multiplying Z_{cs} and Z_{cr} respectively by the neutralizing transformer exciting current (Figure 7) corresponding to these disturbing voltages.

A practical case of considerable importance is that of station ground potential at only one end, combined with longitudinal induction from the same power current. For this case, represented in Figure 6c by $E_r=0$, the longitudinally induced voltage E is 90 degrees ahead of the station ground potential E_s. Thus taking E_s as reference, ($\bar{E}_s=E_s$) equations 5 to 9 reduce to 5a, to 9a, as shown below:

When $E_r=0$ E_s = reference = $\bar{E}_s$ $E=90°$ ahead = $j\bar{E}$

Substituting these quantities in equations 5 to 9.

$$I_s = \frac{jZ_{cp}(1-k)\bar{E} + (Z_{cr}+Z_r+Z_{cp})(jk\bar{E}+\bar{E}_s)}{(Z_{cp}+Z_s+Z_{cp})(Z_{cr}+Z_{cp}+Z_r)-Z_{cp}^2} \quad (5a)$$

$$e_s = Z_{cs} I_s \quad (6a)$$

$$e_r = e_s - j\bar{E} - \bar{E}_s \quad (7a)$$

$$E_{sp} = \bar{E}_s + I_s(Z_s + Z_{cs}) \quad (8a)$$

$$E_{rp} = E_{sp} - j\bar{E} \quad (9a)$$

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which are inherent in solid-type cable when operated in the usual manner. In consequence of the application of this principle of using high gas pressure in conjunction with an oval-shaped cable and the lead-sheath separator, it is possible to operate ordinary solid-type insulation at voltage stresses and conductor temperatures comparable with those used on the oil-filled type of cable.

Experience Abroad

The first commercial circuit of compression cable was installed in England in 1932. The cable used in this initial 66-kv installation was a three-conductor type *HSO* design, that is, a conventional three-conductor type *H* cable with round conductors and binder tape and a triangular-shaped sheath, the latter being obtained by omitting the major portion of the filler material. In order to distribute the diaphragm action as uniformly as possible over the flat sides of the triangular-shaped sheath, a metal binder tape with an asphalted paper tape over and under it, was applied over the sheath. A rectangular steel wire armor applied with a long lay completed the makeup. The armor wires were considered necessary in order to permit the pulling in of a long length of cable without injury. It is the practice abroad to allow these armor wires to take the entire strain of the pull.

While from an electrical point of view this installation has operated satisfactorily since being placed in service, yet on the basis of subsequent experience and laboratory tests the use of the type *HSO* construction has been discontinued abroad and another construction known as type *HSL* has been adopted, because it is easier to manufacture and lends itself better to diaphragm action of the lead sheath. In the latter design three oval-shaped conductors, each separately insulated, leaded and reinforced with several metal tapes, are cabled together with a short lay and armored with steel tape.

In addition to the two designs mentioned, both of which are installed in a steel pipe, a third type known as the self-contained compression cable has been developed abroad. In this design the function of the steel pipe is accomplished by an outer lead sheath which is separated from the diaphragm sheath by a spacer wire to provide a gas channel and is suitably reinforced to withstand high gas pressure. It was at first considered that this design might find some application for duct systems in this country. However, to protect the metallic reinforcing tapes against mechanical damage and corrosion, a third lead sheath would be desirable. With the large conductor sizes commonly employed here, the resulting sheath losses, which cannot easily be prevented, would be excessive. In view of these facts, this type cannot be justified economically.

At the end of 1940 there were over 55 conductor miles of compression cable in service abroad operating at voltages ranging from 50 to 120 kv. Operating experience on these installations has been entirely satisfactory from an electrical standpoint. Electrolytic corrosion of the pipe was experienced on the first installation in England as the result of poor pipe coating, and mechanical trouble near the joint wipes was encountered on a 50-kv installation in Copenhagen because of inadequate provisions for the differential longitudinal movement between cable and pipe.

Because of the difficulty of obtaining precise information on all phases of the foreign installations, and the hazard involved in extrapolating foreign experience to relatively large loads and consequently large conductor sizes normally used in this country, it seemed advisable to recheck fully the mechanical features of the system in the laboratory and in the field by means of an experimental installation.

Preliminary Studies

Diaphragm Action

It was first essential to determine whether the lead sheath could withstand indefinitely the diaphragm action resulting from temperature changes occurring during normal operation of cable. Accordingly extensive laboratory tests were made on pure lead sheath simulating the normal conditions of operation.

It is reasonable to assume that the maximum daily temperature change would be approximately 20 degrees centigrade, which would correspond to a volume change of one-half of one per cent. This about equals the volume difference between an oval-shaped sheath in which the ratio of the minor to major axis is 0.9 and a circular sheath of the same perimeter. Assuming the maximum seasonal change to be 80 degrees centigrade, a volume change of two per cent would occur. To obtain the desired information on the mechanical performance of the lead sheath it was necessary to subject the samples to changes in volume corresponding to both these daily and annual changes. The two per cent volume change would occur once for every 365 of the one-half of one per cent volume change cycles. The test program adopted for most of the measurements consisted in subjecting the samples to one two per cent volume change and 300 one-half of one per cent volume changes in a 24-hour period. This accelerated laboratory test program subjected samples in a single day to the equivalent of approximately one year's diaphram action under normal operation.

Samples of compression cable 32 inches long were used for the tests. The diaphragm action or change of volume was

Table I. Tests of Diaphragm Action of Lead Sheath

Sample Number	External Pressure Medium	Internal Pressure Medium	Type of Cycle	Temp.	Lead Thick. Mils	Origin of Cracks	No. of Cycles to Failure
M-8	*C*	*A*	1/1–2% 4.8 min.	Room	90	Outside	4,900
O-9	*C*	*A*	1/1–2% 4.8 min.	Room	90	Outside	5,800
O-10	*C*	*A*	1/1–2% 4.8 min.	Room	90	Outside	4,500
M-9	*C*	*A*	1/1–2% 4.8 min.	Room	90	Outside	5,000
M-10	*C*	*A*	1/1–2% 4.8 min.	Room	90	Outside	4,100
N-6	*C*	*A*	1/1–2% 4.8 min.	Room	90	Outside	4,460
P-1a	*C*	*A*	1/1–2% 4.8 min.	Room	90	Outside	4,160
O-11	*C*	*A*	1/1–2% 4.8 min.	Room	90	Outside	4,460
O-12	*C*	*A*	1/1–2% 4.8 min.	60 C	90	Outside	4,100
M-11	*C*	*A*	1/1–2% 4.8 min.	60 C	90	Outside	3,100
N-1	*C*	*A*	1/1–2% 4.8 min.	60 C	90	Outside	3,450
P-2a	*C*	*A*	1/1–2% 4.8 min.	60 C	90	Outside	3,500
P-4	*C*	*A*	1/1–2% 20 min.	Room	90	Outside	3,100
Q-1	*C*	*A*	1/1–2% 4.8 min.	Room	80	Outside	3,000
Q-2	*C*	*A*	1/1–2% 4.8 min.	Room	80	Outside	3,200
Q-3	*C*	*A*	1/1–2% 4.8 min.	Room	80	Outside	3,250
O-13	*B*	*A*	1/1–2% 4.8 min.	Room	90	Inside	11,500
O-14	*B*	*A*	1/1–2% 4.8 min.	Room	90	Inside	11,800
O-15	*B*	*A*	1/1–2% 4.8 min.	Room	90	Inside	13,000
O-18	*B*	*B*	1/1–2% 4.8 min.	Room	90	Both sides	24,000
O-19	*B*	*B*	1/1–2% 4.0 min.	Room	90	Both sides	15,240
P-4a	*D*	*B*	1/1–2% 4.0 min.	Room	90	Both sides	17,000

A—Oil initially degassed, but becoming slowly contaminated with air.
B—Degassed oil protected by Syphon diaphragms from air contamination.
C—Compressed air.
D—Nitrogen (water-pumped).

produced by causing pressure differentials between the inside and outside of the cable sheath. At the start of the tests oil, not highly degassed, was used as a pressure medium on the inside of the sheath and compressed air was used directly on the outside. The first eight samples tested on the cycle described gave a life ranging from 4,100 to 5,800 cycles (number of one-half of one per cent volume cycles) at room temperature. Examination of these samples after failure showed evidence that the incipient cracks which occurred had originated on the outside surface of the sheath. Since that surface was in direct contact with the compressed air it seemed likely that oxidation may have influenced the results. Subsequent tests were made in which carefully degassed oil was used as an external pressure medium. This change immediately resulted in a life ranging from 11,500 to 13,000 cycles. Further precautions to insure carefully degassed oil on the inside as well as the outside of the sheath resulted in a life ranging from 15,240 to 24,000 cycles, that is, a life approximately four times as great as that obtained when no precautions against oxidation of the sheath had been taken.

Table I gives the results of laboratory tests on five different kinds of samples (*M, N, O, P, Q*) each representing some change in either sheath thickness, tension of paper tapes during manufacture, or in degree of looseness of armor tapes. In general these structural differences had no significant effect on the life of the sheath.

Samples tested with air as a pressure medium show that thinner sheaths and higher temperatures decrease the ability to withstand diaphragm action. This may be attributed to the effect of oxidation.

The test conditions differed from service conditions in two important respects, namely:

(*a*). That each cycle is carried out in about $^1/_{200}$ the time that would occur in practice.

(*b*). That the volume ranges in the test cycles correspond to load conditions which are possible in service but are not normal for most installations.

In both of these respects, the test conditions are the more severe. The stresses required to produce the same amount of deformation in the sheath are very much less for slowly applied deformation. For a given deformation where the lead is not exposed to oxidation as under service conditions, a greater number of cycles is required to produce failure when the period is long than when it is short. In view of this and the fact that the number of full volume daily cycles per year will generally be less than 300, the approximate 50 years represented by 15,000 cycles is a conservative estimate for the life of the lead sheath.

Longitudinal Movement

The usual practice for armored compression cable is to anchor the joints; however, it was felt that if the armor were eliminated, and the three conductors cabled with a comparatively short lay, the longitudinal movement would be restrained without undue stress on the cable or joints. The following is a brief account of the tests designed to measure the magnitude of such restraining forces.

The three conductors of a 50-foot section of 600,000-circular-mil unarmored compression cable were cabled to a six-foot lay, but not bound together, and then pulled into a six-inch inside diameter iron pipe of the same length. At one end the cable was anchored to the pipe, at the other end means were provided for applying and measuring a restraining force of such magnitude as to prevent any movement of the cable with respect to the pipe end. The cable was heated by circulating current in the conductors. Thermal equilibrium was reached with conductor, sheath, pipe, and ambient air temperatures of 83, 67, 43 and 23 degrees centigrade, respectively. The maximum restraining force required to prevent longitudinal movement during the thermal transition period was 475 pounds, which dropped to 350 pounds when the steady-state temperatures were reached.

In view of the very small forces developed by the cabled conductors, a similar test was made on the same type of cable, in which the conductors were not cabled or bound together in any manner. The final restraining force was 3,000 pounds, with a maximum of 3,500 pounds reached during the transition period, for a final conductor temperature rise of 66 degrees centigrade.

The cable sample above described was then bound by hand with heavy duck tape and tested. The maximum force reached was 4,500 pounds for a final conductor temperature rise of 59 degrees centigrade.

These test results show that when the three conductors of a compression cable are cabled together in a lay of about six feet, but not bound, the longitudinal forces due to restrained thermal expansion are so low that no expansion bends are necessary. This was further verified by the field tests. On the other hand, if the conductors are bound together, either straight or twisted, or kept straight without binding, the forces developed are large enough to endanger joints of usual design.

Outer Coverings

A test was made to determine the ability of duck tape, applied over the outer lead-sheath reinforcing tapes of an unarmored compression cable, to withstand the friction incident to pulling this type of cable into steel pipe. It was observed from laboratory tests that very thin tape was damaged in moving through the pipe even in a short distance of 50 feet. One of the samples used for test was covered with a 20-mil duck tape with salvage. This sample was pulled in and out of the pipe until parts of the sample had been subjected to the same amount of abrasion as would have been received if the cable had been pulled through a 2,000-foot section of pipe. Examination of the sample showed that the heavy duck tape was uninjured.

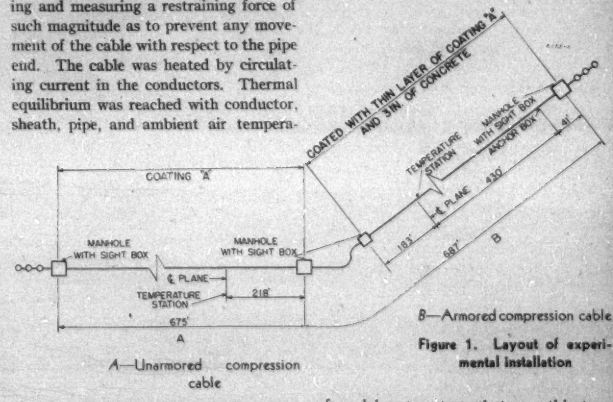

Figure 1. Layout of experimental installation

Experimental Installation

General Layout

The experimental circuit of the compression cable, shown in Figure 1, con-

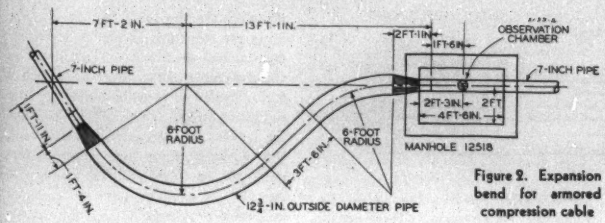

Figure 2. Expansion bend for armored compression cable

sisted of two cable sections each about 700 feet long, one armored and one unarmored, installed in a welded steel pipe. The two sections were connected by means of a joint, and their free ends were provided with terminals for parallel connection with an existing 120-kv overhead line. Suitable equipment was provided for artificially loading the cable by circulating current through the two cable sections with the overhead line providing the return path.

The Pipe Line

Electrically welded steel pipe having an outside diameter of seven inches and shipped in double random lengths was used for this installation. The ends of each length were expanded and beveled for use with chill rings. In the field gas welding was used, and the welds were tested at 500 pounds per square inch air pressure.

The terminal ends were housed in 3⅛-inch outside diameter 0.120-inch wall copper pipes which were fitted and wiped into the trifurcating heads on the ends of the steel pipe line.

The pipe system was provided with nitrogen feeding equipment consisting of a standard cylinder of oil-pumped nitrogen and a gas-pressure regulator with pressure gauges. The line was equipped with a low gas-pressure alarm set for a pressure of 150 pounds per square inch.

The Expansion Bend

An expansion bend was installed near the end of the armored cable in order to protect the joint between the armored and unarmored compression cables from the longitudinal thrust exerted by the armored cable. Figure 2 shows the expansion bend used in this installation, which was made of 12-inch steel pipe with reducers on both ends. The usual practice abroad is to use an expansion bend on each side of the joint.

Corrosion Protection Coverings

The pipe on the unarmored compression cable was given a coating of a material used extensively for pipe covering. This coating, designated as coating *A*, consisted of: a hot application of wax, a spiral wrapping of reinforced asbestos, a hot application of a service coat incorporating natural asphalt, a spiral layer of a single membrane wrapper, and a spiral wrapping of heavy kraft paper. The wax was an adherent coating, chemically and mechanically fortified.

On the armored section concrete was applied around the pipe in the trench to a minimum thickness of three inches.

Cable Design

The armored cable was of conventional design as used abroad. The three 650,000-circular-mil Compack oval conductors were shielded and insulated with 500 mils of impregnated paper. The insulation on each conductor was shielded and covered with 85 mils of lead. There was applied over each sheath three paper tapes, two reinforcing bronze tapes, and two saturated cotton tapes. This assembly was cabled with saturated jute fillers and covered with a heavy saturated duck tape, jute bedding and galvanized steel-wire armor.

The individual legs of the unarmored cable were of the same construction as those in the armored cable, with the addition of two 30-mil presaturated canvas tapes. These legs were cabled without fillers or further finish. Figure 3 shows a sectional view of the unarmored compression cable installed in a steel pipe having an outer protective covering.

Anchoring of the Cables

The armored compression cable was anchored at two points:

1. At the joint with the unarmored cable, to prevent the joint from being moved by the expansion of the cable. Due to proximity of the expansion bend no large forces were involved.

2. At a point approximately 40 feet from the terminal end the armor wires were so anchored as to withstand large longitudinal forces in either direction. The expansion occurring in the 40-foot section was calculated to be negligible and would be taken up by the bend of the cables in the riser pipes. Therefore, at the joint between the terminal ends and the armored cable the armor wires were simply bound in place.

With the above arrangement of anchorage, a longitudinal movement roughly equal to that obtained in a 1,400-foot-long armored compression cable will take place in the direction of the expansion bend and joint between the armored and unarmored compression cables. To observe this movement a removable sight glass with reference mark was installed in the pipe near the end of the expansion bend as well as at other points in the line where such observation would be of use. The cable under each sight glass was equipped with a graduated scale which was fitted in proper position after the cable was placed in its final location.

Normal Joints

Figure 4 shows the normal joint used between the armored and unarmored sections of cable. Figure 5 shows the detailed design for each phase.

The design of the normal joint is of particular interest, because it achieves the connecting of two sections of cable without any appreciable structural change at the point of joining. The design results in a joint that is simple, reliable, and of very small diameter, yet similar in construction to those used on high-voltage single-conductor solid-type cables. Very little schooling is therefore necessary for splicers well-versed in solid-type cable jointing to enable them to construct this joint. Diaphragm action takes place along the joint in a manner similar to that of the cable.

Soldered-type countersunk copper connectors were used with an outside dimension the same as that of the cable conductor. Semiconducting tapes were used to shield the connectors and applied so as to make good contact with the conductor shielding tapes. Long pencils

Figure 3. Sectional view of unarmored compression cable installed in steel pipe having an outer protective covering

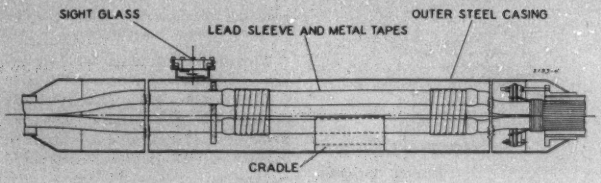

Figure 4. Normal joint between armored and unarmored sections of compression cable

were made on the factory insulation by tearing each tape individually at points one-eighth inch apart. Impregnated-paper tapes were tightly applied, butt-lapped, and wrapped in the same direction, until the thickness of the hand-applied insulation exceeded that of the factory insulation by 20 per cent. Shielding braid was applied over the insulation. The diameter was so made that it required considerable force to draw the oval sleeve over the joint core. The joint core was coated with cable oil before forcing the sleeve in place. This made the sleeve over the joint insulation fit as snugly as the regular sheath over the factory-applied insulation. The sleeve was then beaten down at the ends and wiped to the cable sheath. It was then reinforced with brass tapes similar to the reinforcing on the cable proper. After the individual joints were completed, they were tied together, the steel joint casing pulled over and welded in place.

Laboratory tests had been made previously on two joints of this design. The man making these joints had had no previous experience in making paper-taped joints other than a single similar practice joint. The voltage program as specified in the Association of Edison Illuminating Companies Specification for Oil-Filled Cable was used with the time reduced for the first step to $1^1/_2$ hours, and the 20 per cent increase in voltage every three hours obtained in small steps every ten minutes instead of one large step at three-hour intervals. Breakdown voltages, expressed in volts per mil of cable insulation, of 436 and 445 were obtained. In both joints the breakdown was radial and over the connector; there were no other signs of stressing. These results compared favorably with values obtained on standard normal oil-filled cable joints of this voltage class. These laboratory values are probably very conservative as compared with what might be expected from the field joints where a more nearly circular connector was used, and where the tapes were applied with greater tightness by experienced splicers.

Terminals

Figure 6 shows the design of the terminals used on the experimental line. These terminals have a brass-fitted bakelite stop-tube assembly of sufficient strength to withstand the high internal operating pressure of the cable oil. This stop-tube assembly ends in a stem at the upper end and a flange at the lower end. The porcelain insulator, with a barrier assembly and stress cone, metal rings at top and bottom, and an insulator cap, is placed over the stop tube and bolted to the flange. The space between the stop tube and the porcelain is filled with oil. The terminal is essentially the same design as that used for oil-filled cable with the addition of the stop tube.

Compensators

Compensators were used in order to allow for the expansion and contraction of the impregnating oil contained in the rigid stop tubes of the terminals, and thereby prevent overworking the sheath near the ends of the compression cable. The compensator may be described as a flexible membrane in a housing which is capable of withstanding 200 pounds per square inch pressure. The membrane separates the housing into two chambers; one containing oil is in direct communication with the inside of the stop tube, and the other containing nitrogen is connected to the pipe line. Expansion of the oil in the stop tube and cable due to increasing temperature is accommodated by the movement of the membrane which is spring-loaded to provide a characteristic similar to that of the cable sheath. During cooling the process is reversed, and thus complete impregnation of the terminal at all times without appreciable interchange of oil between the terminal and cable is insured. One compensator is connected to each terminal.

Installation

Methods usually employed for pulling cables into ducts were readily adapted to the installation of the compression cable in the steel pipe. At the start of the installation of the armored compression cable, high pulling stresses (16,000 pounds) were experienced on the pulling line when it passed around the expansion bend located at the pulling end of the section. As soon as the armored cable started to pass through the expansion bend, the pulling stresses on the line became normal.

A maximum pull of 7,800 pounds was experienced during the installation of the unarmored cable. This corresponds to a coefficient of friction of about 0.54. For future installation of unarmored compression cable where an even lower pulling stress is desired, a half-round copper wire wound over the fabric tapes of the individual cables can be employed.

In order to determine the effect on a

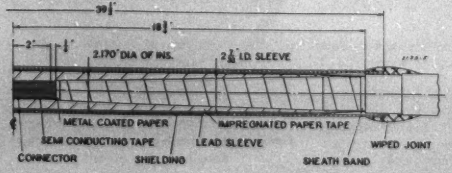

Figure 5. Detail for one conductor of the normal joint

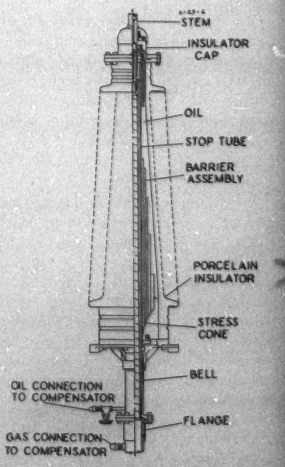

Figure 6. Terminal for 120-kv compression cable

compression cable of nitrogen coming in contact with the insulation, the lead sheath of one phase of the unarmored cable was perforated with holes approximately one-eighth inch in diameter at 25-foot intervals throughout its length.

Before the cables were pulled into their respective pipe sections, the piping was dried with hot air. After the cable was installed the pipe was evacuated and then filled with nitrogen at a low positive pressure. With the help of temporary seals, this nitrogen was kept in the pipes until the cable-splicing operations were completed, at which time the pipe was filled with nitrogen gas at a pressure of approximately 200 pounds per square inch. The nitrogen used was oil-pumped, guaranteed to contain less than 0.3 per cent oxygen and 0.03 per cent water.

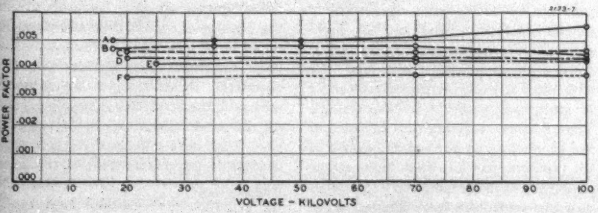

Figure 7. Curves of power factor versus voltage

Curve	Date (1941)	Cable Temperature (Degrees Centigrade)
A	March 29	9.6
B	May 7	14.0
C	May 17	14.8
D	May 27	19.9
E	July 8	20.9
F	August 6	23.5

Tests on the Cable Before Installation

As the compression cable before installation is essentially a standard solid-type cable, routine factory acceptance tests, usually performed on solid-type cable of similar insulation thickness, were considered adequate for detection of nonuniformities. The impulse strength of compression cables had been determined by previous tests,[2] and calculations showed that this cable would fail at a voltage in the neighborhood of 1,100 kv. A sample of compression cable used in this installation withstood without failure impulse voltages up to 900 kv (the capacity of the generator). This is well above the 138-kv insulation level.

Field Tests

After the installation had been completed the cable was subjected to repeated load cycles, and periodic measurements were made of the power factor and movement of the cable within the pipe.

During the time that the cyclic loading tests were in progress (a little over five months), the cable line was subjected to 54 load cycles with load on for $2^1/_2$ hours and load off for $2^1/_2$ hours, and 249 load cycles with load on for 4 hours and load off for 4 hours. In addition, a number of cycles was used in which the load was applied for durations ranging from approximately 13 hours to 190 hours. During the majority of the load cycles, the current ranged from 500 to 550 amperes (or 10 to 20 per cent above the nominal 95,000-kva rating of the line); during others, particularly those of the longer duration, the currents ranged from 460 to 510 amperes.

The first few heating cycles produced a movement of seven-eighths inch in the armored cable at the entrance to the expansion bend over 613 feet of cable and a slight initial adjustment of position of the unarmored cable. Subsequent heating and cooling cycles produced a cumulative $3^3/_4$-inch movement of the armored cable and no appreciable movement (one-eighth inch) of the unarmored section. This indicated that without armoring, the cables would absorb the longitudinal movement, thus making expansion bends unnecessary. During the recent cold season and without load, the armored cable has returned to its original position.

Power-factor measurements were made on each conductor of the two connected sections at voltages from 20 kv to 100 kv to ground. An initial set of measurements was made before starting the load cycles, and subsequent measurements made at intervals during the period that the cable was under test. It was not practical to obtain the power factor of the test cable at elevated temperatures due to the relatively long time necessary to switch the test cable out of the circuit and connect up the power-factor measuring equipment. The measurements were made after the cable had been de-energized for a period of 15 hours or more.

These power-factor measurements as obtained on one of the conductors are shown in Figure 7. There was no significant difference in the measured values for the different conductors. It will be seen that there is a slight decrease in power factor in the later readings which were at slightly higher temperatures than the initial set.

No noticeable difference in power factor was apparent in the phase with holes in the sheath as compared to the other two phases. However, this cable has not been operating long enough to prove this point definitely.

Summary

1. Methods normally used for pulling cables into ducts can readily be adapted to the installation of compression cable in steel pipe.

2. Conditions in this country make it possible to eliminate the armor which is used on compression cable abroad.

3. By cabling the individual lead-covered and reinforced conductors with a suitable lay, longitudinal expansion becomes of no practical importance, and expansion bends as used abroad can be eliminated.

4. Diaphragm action of the lead sheath when in nitrogen shows indefinite life under simulated operating conditions.

5. Compression cable is well suited for handling loads in the range of 100,000 kva.

6. The experimental installation which has been installed for approximately one year shows no deterioration of the insulation even on the phase with the lead sheath perforated every 25 feet.

References

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120-Kv High-Pressure Gas-Filled Cable

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THIS paper deals with the theory, manufacture, and testing of high-pressure gas-filled cable and describes an experimental installation by the Detroit Edison Company in co-operation with the General Cable Corporation and a subsequent commercial installation on the Detroit Edison system.

While high-pressure gas-filled cable has been in successful operation in England, these are the first experimental and commercial installations in the world of this type cable in a steel pipe. The installation of such cable in a steel pipe involves the removal of the lead sheath in the field, thus exposing the insulation to the atmosphere and to the possibility of mechanical injury during installation. Since the effect of such conditions is difficult to determine in the laboratory, the experimental installation was made.

The commercial line was subsequently installed on the Detroit Edison System and put in operation on December 31, 1941. This line is seven miles long and designed to transmit 95,000 kva continuously at 120 kv.

Experience Abroad

High-pressure gas-filled cable has been in successful operation in England since 1937 at which time installations of cable of this type were made for operation at 33 kv and 132 kv. Today there are approximately 25 conductor miles in successful operation at voltages ranging from 33 kv to 132 kv and at pressures from 50 to 225 pounds per square inch. These cables[1] are equipped with lead sheaths reinforced so as to withstand the operating gas pressure.

The high-pressure gas-filled cable makes effective use of the well-known fact that the dielectric strength of gas increases very greatly with pressure. The great gain possible by the use of high gas pressure in cable insulation has long been recognized. However, it was not until a more complete knowledge of other facts became available that effective use could be made of this principle.

The low permittivity and dielectric loss of unsaturated paper made the use of this dielectric seem most promising. Many of the expected results were realized in cables made in this way; dielectric losses were very low, and there was no ionization at voltages well above operating voltage. However, the short-time and impulse breakdown voltages were very low. Since there was no measurable ionization at voltages just below failure it seems that complete breakdown in such a cable follows promptly after the smallest amount of ionization.

An entirely satisfactory solution of the problem has been found by combining several features. The use of high-density low-porosity paper presaturated with a high-viscosity compound has eliminated the quickly destructive effect of ionization produced by overvoltage. These features, together with shielding of the conductors as advocated by two of the authors for all very high-voltage cable,[2] and with the use of very thin tapes near the conductors, have resulted in obtaining an insulation entirely free from ionization up to about twice operating voltage and a dielectric strength (short-time or long-time) in the same range as for oil-filled insulation. Perfection of methods of drying and saturation, the use of a saturant of very low loss, and the prevention of moisture absorption during taping have also resulted in extremely low dielectric loss and a high degree of uniformity throughout the thickness of the insulation.

Two different types of saturant have been used abroad. In the earlier ones, the saturant contained a very large percentage of rosin and had a very high viscosity. However, it also had a high power factor and for this reason was not considered entirely satisfactory. In later cables the saturant has been petrolatum. This has a low loss and does not migrate at a temperature below its melting point of 50 or 55 degrees centigrade, but does become very fluid at temperatures at which cables may operate in this country. Thus neither of these saturants was entirely satisfactory particularly for a pipe cable installation. The saturant used in the Detroit cables has a very high viscosity, possesses extraordinarily good stability, and gives a cable of as low dielectric loss as for the best of modern power cables. The good results obtained on these cables are attributable in no small part to the development and use of this saturant.

The value of the very thin tapes and of the conductor shielding lies primarily in the increase of specific dielectric strength of gas in very thin films. Because of the lower dielectric stress farther from the conductor, the thin tapes are required only near the conductor. Thus by grading the paper-tape thickness, the same dielectric strength is secured for the cable as if all the paper were thin; at the same time there is secured greater freedom in the penetration of gas and more rapid equalization of the pressure through the insulation wall. Moreover, the resulting cable withstands without damage the normal bending in manufacture and installation, as it could not do so fully if made entirely of the thinnest paper.

Nitrogen has been selected as the pressure medium, because of its good dielectric properties, its complete inertness with respect to the materials used in the cable, and its commercial availability with low moisture and oxygen content.

The SMD Type Cable

The previous paragraphs dealt with the basic principles behind the high-pressure gas-filled cable and apply to this type cable as manufactured in England and to the pipe type of cable manufactured in this country and hereafter designated as *SMD* type. The difference in construction is in the outer enclosure. Abroad a reinforced lead sheath is used over the insulated conductors to provide this gas-tight enclosure. An additional lead sheath is usually employed to protect the reinforcements. The *SMD* type of high-pressure gas-filled cable retains the essential insulation of the reinforced lead-sheath type but does away with the permanent lead sheaths as used abroad. All three phases of even the largest-size cables are installed in one common pressure chamber. This pressure chamber is a steel pipe which is in itself gas-tight, and which is designed to withstand the required pressure. A lead sheath which

Paper 42-135, recommended by the AIEE committee on power transmission and distribution for presentation at the AIEE summer convention, Chicago, Ill., June 22-26, 1942. Manuscript submitted April 11, 1942; made available for printing May 20, 1942.

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The authors wish to acknowledge the contributions of S. M. Dean, Detroit Edison Company, who suggested the use of a steel pipe as the pressure container in this installation, instead of the customary reinforced lead sheath. They are indebted for the valuable assistance given by their other associates in the Detroit Edison Company and the General Cable Corporation, and wish especially to thank W. S. Brown, F. G. Cox, R. C. Fellows, H. G. Hall, E. Johansson, L. Meyerhoff, J. D. Piper, E. Richman, W. D. Sanderson, G. J. Shurts, and J. Sticher.

serves as a protective covering during shipment and storage is removed as the cables are installed.

While the insulation of the *SMD* type cable is the same as for the reinforced sheath type, the removal of the lead sheath requires that a covering be placed over the insulation for protection during installation. In the cable used in the experimental line this was accomplished by the application of a strong canvas tape over the insulation shielding tapes. The cable for the commercial line was manufactured with a half-round copper wire over the canvas tape to increase the mechanical protection and reduce the coefficient of friction between the cable and pipe.

Since the installation of this type of cable requires the removal of the lead sheath in the field, the exposure of the insulation to the atmosphere, and the possibility of mechanical injury during installation, it was felt that an experimental installation was essential to demonstrate the practicability of installing this type of cable in a commercial line.

While the superiority of insulation made with graded tapes of five mils and less was recognized, the question of whether or not an insulation built from papers of standard thickness, five mils or over, would be satisfactory was raised. To obtain an answer to this question, it was decided to employ all five-mil tapes in the *SMD* type cable used in the experimental line. The five-mil thickness was used to facilitate taping and to depart as little as possible from the standard practice used in the manufacture of power cables. In the cables built subsequently for the commercial *SMD* line, grading of paper thickness was employed, thus conforming to the practice abroad.

Manufacture

The cable in the commercial installation was of the following construction: single conductor 600,000 circular mils concentric round strand, 600 mils preimpregnated wood-pulp paper of graded thickness from $2^1/_2$ to 5 mils, two metal-faced paper tapes applied next to the conductor, and two metal-faced tapes over the insulation (all metal-faced tapes included in the 600-mil wall thickness), bronze shielding tape intercalated with a saturated muslin tape, one 20-mil paraffin saturated tape, one half-round 200- by 100-mil copper wire applied in open spiral, and a 94-mil temporary lead sheath. Figure 1 shows a sectional view of this cable installed in the steel pipe having an outer protective covering.

Before being applied to the cable, the paper tapes were dried and saturated with an oil having a viscosity of 3,000 seconds Saybolt Universal (50 centipoises) at 100 degrees centigrade. The preimpregnated-paper tapes were wrapped on the conductor in a standard taping machine and in the usual manner, except that the entire machine was enclosed in a room where in the relative humidity was maintained below 20 per cent regardless of outside atmospheric conditions. This humidity control, together with precautions taken during impregnating, handling, and storing, greatly reduced the moisture content in the finished cable.

The cable for the experimental installation differed from the above only in the omission of the half-round copper wire, the use of five-mil paper tapes throughout, and the application of paper tapes without humidity control.

Specification

SMD type cable may be tested in accordance with the Association of Edison Illuminating Companies Specification for Oil-Filled Cable, provided that during the electrical tests an internal nitrogen pressure of 30 pounds per square inch is maintained on commercial lengths and 225 pounds per square inch on samples. The temporary lead sheath on the commercial lengths should, of course, be of sufficient strength to withstand this pressure.

Experimental Installation

The experimental circuit of *SMD* type cable consisted of one section of cable of approximately 700 feet in length with normal joints at each end connecting to the terminal end cables. Terminals were provided at each end for connection with an existing 120-kv overhead line. The cable was installed in a seven-inch-outside-diameter welded steel pipe having a wall of 0.231 inch and filled with nitrogen gas at a pressure of approximately 200 pounds per square inch. The pipe section housing the cable was provided with manholes at each end at which points sight boxes were provided for observing cable movement.

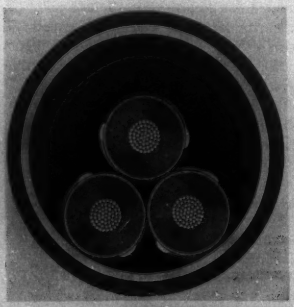


Figure 1. Sectional view of SMD type cable installed in a protective-coated steel pipe

Two different types of protective coverings were applied to the pipe. About half of this 700-foot section was covered with a coating of plasticized coal-tar enamel. Joints in the pipe were hand-coated with the same material. The balance of this section of pipe was covered with Somastic. This material consists of a primer coat over which was extruded, hot, a half inch of asphalt mastic material.

The joints and terminals were of the same general design as used on the commercial line and are described hereafter.

Since it was desirable not to expose the insulation to the atmosphere any longer than necessary, a mechanical stripping device was designed which folded the lead sheath back as the cable was pulled into the pipe. V-shaped grooves were made in the lead sheath during the lead covering process in order to facilitate stripping. It was found, however, that scoring of the lead sheath by hand in the field was still necessary, and that mechanical stripping increased the pulling stresses considerably. It was thus unnecessary to score the lead at the factory, as scoring in the field was all that was required to facilitate this operation.

Field Tests

Measurements were made after the installation had been completed in order to determine what effect cyclic loading of the cable would have on the power factor of the insulation and what movement of the conductors would take place.

The cable which was connected to the 120-kv overhead line was subjected to load cycles by the circulation of current through the conductor with the overhead line acting as the return path. During the first 54 cycles the load was on for $2^1/_2$ hours and off for $2^1/_2$ hours. This was followed by 249 cycles of longer duration with the load on for 4 hours and off for 4 hours. In addition there were a number of cycles in which the load was applied for durations ranging from 13 to 190 hours. For the majority of the load cycles the current ranged from 500 to 550 amperes (or 10 to 20 per cent above the nominal 95,000-kva rating of the line). The maximum change in copper temperature

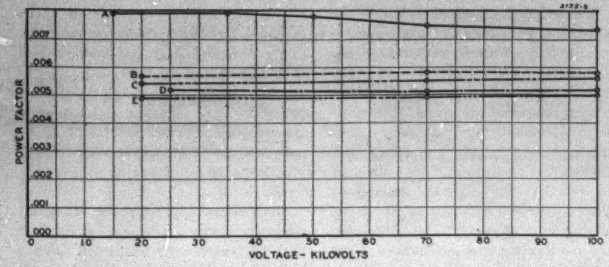


Figure 2. Curves of power factor versus voltage for experimental installation

Curve	Date (1941)	Cable Temperature (Degrees Centigrade)
A	March 29	2.6
B	May 17	19.6
C	May 27	22.3
D	July 2	25.8
E	August 6	27.7

that occurred during this period of loading was 58 degrees centigrade.

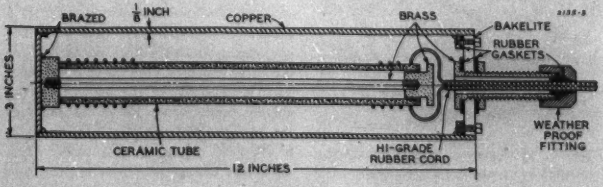
The above load cycles produced only a slight initial adjustment in the position of the cable, and no further movement of the cable occurred thereafter. This indicates that there is sufficient space in the pipe to absorb the longitudinal thermal expansion.

Power-factor measurements were made on each of the three conductors at voltages from 20 kv to 100 kv to ground. An initial set of measurements was made before loading and repeated at intervals during the period that the cable was being subjected to the loading cycles. The measurements were made after the load had been removed from the cable for a period of 15 hours or more. It was not feasible to obtain power-factor measurements at elevated temperatures, since it required a relatively long time to switch the experimental cable out of the circuit and connect up the power-factor measuring equipment.

The power-factor data as obtained on one of the conductors are shown in Figure 2. There was no significant difference in the measured values for the different conductors. It will be noted that the later power-factor values are noticeably lower than the earlier ones. The first tests were made at 2.6 degrees centigrade, and the last one at 27.7 degrees centigrade. This is entirely consistent with laboratory data, which show that in the lower range of temperatures the power factor of the insulation decreases as the temperature increases. These measurements show no evidence of deterioration of the insulation.

Figure 3. Cell for measuring thermal resistivity of soil

Ceramic tube wound with Chromel wire to dissipate 200 watts at 120 volts



Soil-Resistivity Measurements

During the period that tests were being conducted on the experimental installation, soil-resistivity measurements were made for use in designing the commercial line. Measurements were made to determine the thermal resistivity of the earth under varying seasonal conditions and for different types and conditions of soil. A cell was used consisting of a copper cylinder twelve inches long and three inches in outside diameter, with a one-eighth-inch wall, and equipped with an internal electric-heating element. This heater was capable of dissipating 200 watts at 120 volts, uniformly over the walls. A copper-constantan thermocouple was embedded in the mid-point of the cylinder wall. The general construction of this cell is shown in Figure 3.

This cell was buried vertically in the ground; the heater supply and thermocouple leads were brought out to a convenient point. Means were also provided for measuring the ambient earth temperature nearby. Sufficient energy was supplied to the heater element to cause a 40- to 50-degree-centigrade rise between cylinder wall and ambient earth. For the soils so far tested an input of 50 watts has been necessary.

The earth thermal resistivity (in degrees centigrade per watt per centimeter cube) may be computed from the formula $g=(128/W)(T_1-T_2)$: when W = watts input, T_1 = temperature of cylinder wall, and T_2 = temperature of ambient earth. This formula is empirical and was derived by comparison with the results obtained from such a cylinder with those obtained with a sphere.[3]

Figure 4 shows values of resistivity for three types of soil encountered along the route of the commercial line, as well as the variations in resistivity that are caused by the changes in moisture content during the different seasons of the year.

Tests with the thermal resistivity cell at what will probably be the locality where the soil has the highest thermal resistivity along the commercial line (in fine sand) show maximum average values of 120 during the dry season. In other areas where loam prevails, maximum average values of 95 and 75 were measured during the dry and wet seasons, respectively. Corresponding measurements where heavy clay prevails show resistivities of 105 and 95, respectively.

Commercial Line

General Layout

The commercial line consists of a seven-mile circuit installed under paved city streets. The cable used has previously been described under "Manufacture" and was shipped and installed in lengths of approximately 1,500 feet. The pipe line consisted of seven-inch steel pipe protected from corrosion by means of Somastic pipe covering. The line is sectionalized by stop joints, one near each termination and four at intermediate points, thus dividing the line into five approximately equal sections. These stop

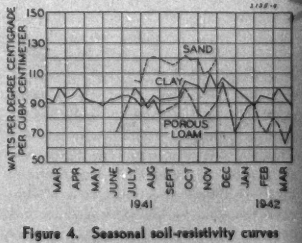


Figure 4. Seasonal soil-resistivity curves

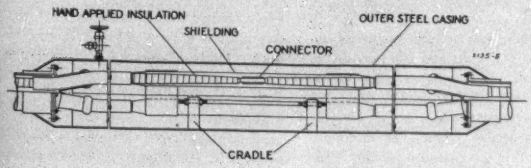


Figure 5. Normal joint for *SMD* type cable

joints are provided so that if repairs to the steel pipe are required, because of corrosion or for other reasons, it will be necessary only to discharge the nitrogen from the section involved. Sectionalizing the line also facilitates the location of a gas leak in the steel pipe if a leak should occur. In normal operation the stop joints are by-passed by a pipe containing a valve which may be closed for sectionalization. Nitrogen tanks were connected through pressure regulators to the ends of the pipe to take care of any leakage. A low pressure alarm was installed to operate when the gas pressure drops to 150 pounds per square inch.

Installation

The temporary lead sheath was scored and stripped by hand, as the three cables were pulled as a unit into the steel pipe. No difficulty was encountered in pulling these 1,500-foot lengths. The maximum pulling stress that occurred on any of the sections was 7,200 pounds which corresponds to a maximum coefficient of friction of 0.37.

For a distance of approximately 15 feet on each end of the cable sections, the lead sheaths were allowed to remain to facilitate making the joints, and to permit sealing the cables in the steel pipe during installation. The cables were sealed in the pipe by means of trifurcating heads, which consisted of a flange and gasket bolted to the pipe ends and three lead nipples wiped to the cable sheaths.

Previous to pulling in the cable, each section of pipe line between manholes was tested for leaks with 500 pounds per square inch air pressure for 24 hours. The pressure was then released, and the pipe filled with dry nitrogen gas at a pressure of 5 to 10 pounds per square inch. This pressure was maintained until the cable was pulled. After the cable was pulled, the ends of each section were sealed by means of the trifurcating heads, and dry nitrogen gas admitted at a pressure of 5 to 10 pounds per square inch. After each section between stop joints was completed, it was evacuated. When all sections of the line were completed, the line as a unit was filled with dry nitrogen gas at 200 pounds per square inch.

Normal Joints

The normal joints, shown in Figure 5, are essentially the same in the experimental and commercial lines and were hand-taped with presaturated paper. Soldered-type countersunk copper connectors having a diameter the same as that of the cable conductor were used. These avoid the regions of high stress that occur near the ends of standard connectors. Stress control was further improved by the use of semiconducting tapes for shielding the connectors. These tapes were applied so as to make good contact with the conductor shielding tapes. Long pencils were made on the factory insulation by tearing each tape individually at points approximately one-eighth inch apart. The paper tapes were applied butt lap to a thickness 20 per cent greater than that of the factory-applied insulation.

The hand-applied insulation was tapered at the ends of the joint by tearing the successive tapes at points $^{9}/_{16}$ inch apart. The joint was completely shielded with tinsel copper braid. Special rubber sleeves were temporarily pulled over the completely insulated and shielded joints to protect them against dirt and moisture and to permit maintaining low gas pressure on the insulation. The ends of these rubber sleeves were sealed with rubber tape to the short sections of lead sheath left on the cable ends. After all three joints were completed, the rubber sleeves were removed, the wipes at the trifurcating heads melted off, the trifurcating heads moved two inches from the pipe ends and the wipes remade. This procedure permitted entrance of gas into the joint casing and anchored the cables at the joint. The enlarged section of pipe forming the joint casing was then pulled over the joint and welded in place.

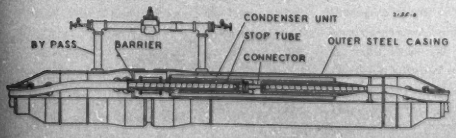


Figure 6. Stop joint for *SMD* type cable

Stop Joints

The stop joint, shown in Figure 6, is essentially the same as those used for oil-filled cable. The stop tubes have somewhat greater wall thickness to give strength to withstand safely a differential pressure of 225 pounds per square inch. At one end the three stop tubes are sealed to a diaphragm through which the cables pass. This diaphragm is sealed to the outer joint casing. The condenser unit for each of the three individual joints is similar to the condenser for oil-filled cable except that it is wound with preimpregnated paper, and no individual oil-tight outer sleeves are used. This allows the gas to come into direct contact with the insulation of the condenser, thus improving its dielectric strength in the same manner as for the cable proper.

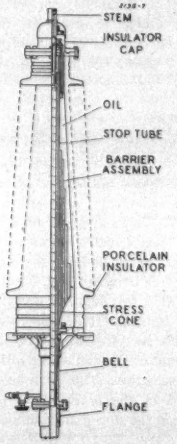


Figure 7. Terminal for *SMD* type cable

Terminals

The terminals used on both the experimental and commercial lines have a brass-fitted bakelite stop-tube assembly similar to those used in the stop joints but of greater length. This stop tube assembly ends in a stem at the upper end and a flange at the lower end. The porcelain insulator, with a barrier assembly and stress cone, metal rings at top and bottom, and an insulator cap, is placed over the stop tube and bolted to the flange. The space between the stop tube and the

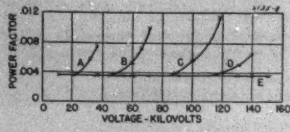


Figure 8. Ionization tests at different gas pressures on 600,000-circular-mil cable with 600-mil insulation

Curve	Pounds Per Square Inch
A	0
B	50
C	100
D	150
E	200 and 225

porcelain is filled with oil. Thus the terminal is essentially that used for oil-filled cable with the addition of the stop tube. The terminals are installed in a manner similar to single-conductor terminals on oil-filled or solid-type cables. Figure 7 shows the design of these terminals.

Manholes

The 24 normal and 6 stop joints were housed in manholes having brick walls, concrete floors, rail-supported brick ceilings, two chimneys, and built-in pulling eyes. The normal joint manholes were 12 feet long, 4 feet 9 inches wide, 5 feet high, and those housing the stop joints were 17 feet 10 inches long, 5 feet 6 inches wide and 5 feet high. Corrugated galvanized-iron culverts, concentric with the pipe, were used for storing the steel-joint casings out of the way of the splicers during construction. One such culvert was provided in the normal-joint manholes and two in the stop-joint manholes.

Laboratory Tests

Power Factor Versus Pressure and Voltage

The effect of different gas pressures on the power factor at different voltages is shown in Figure 8. This cable operates at approximately 70,000 volts to ground and was designed to show no measurable ionization at double working voltage, or 140,000 volts, when under a nitrogen pressure of 225 pounds per square inch. In general, there was no appreciable ionization at 140,000 volts and 200 pounds per square inch. It is apparent also that at approximately 80,000 volts and 100 pounds per square inch, no appreciable ionization occurs. Thus the minimum safe operating gas pressure for this cable is approximately 100 pounds per square inch. Ionization data on this lot of cable may be summarized as indicated in Table A.

Table A

Gas Pressure (Lb. Per Sq. In.)	Voltage at Which Ionization Begins
Atmospheric	Approximately 23 kv
50	Approximately 50 kv
100	75–90 kv
150	100–120 kv
200	120–140 kv
225	140 kv or above

Compound Migration

The fact that this cable was to be installed in a steel pipe without a lead sheath made it necessary to determine whether at high temperatures the impregnant would flow out of the paper into the pipe, or when installed vertically, the compound would flow longitudinally of the cable. If such migration would be harmful, the effect would become apparent from ionization tests. In Figure 9 are curves showing ionization tests on a sample of cable after heating for 65 days at 100 degrees centigrade in an inverted U position. The sample in the bent position had an over-all height of 15 feet of which only a very small part was consumed by the storage of the small amount of drained compound at the lower ends in the space between the lead sheath and insulation. This offered as complete an opportunity for drainage as for a cable of any height. The cable was allowed to cool for eight hours each day for 38 of the 65 days. Initially and also after 43 days' heating there was no ionization at 140 kv and 225 pounds per square inch, but after 65 days' heating ionization started at 130 kv. Thus it is safe to assume, since there was no change after 43 days' heating at 100 degrees centigrade, and only a slight change after 65 days' heating, that migration is not a problem at normal operating temperatures even in vertical runs.

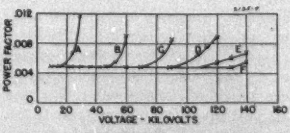


Figure 9. Ionization tests at different gas pressures on 600,000-circular-mil cable with 600-mil insulation, after being heated for 65 days at 100 degrees centigrade in an inverted-U position

Curve	Pounds Per Square Inch
A	0
B	50
C	100
D	150
E	200
F	225

Radial Power Factor

It has been customary in the industry to measure radial power factor at 60 degrees centigrade. In order to exaggerate effects on power factor of small quantities of contaminants, notably moisture, radial power factor tests on *SMD* type cable were made at 80 degrees centigrade. The greater sensitivity of measurements at 80 degrees centigrade, as compared with 60 degrees centigrade, is markedly shown in Figure 10 where curves *C* and *D* show radial power factor at these respective temperatures. The sample of cable used for these measurements was an experimental section made before the procedure used in the construction of this type of cable had been perfected.

Figure 11 shows the very high degree of correlation that exists between the power factor and moisture content. The radial moisture-content curve has been superimposed on the radial power-factor curve, and the variations in the moisture content are closely followed by variations in the power factor. These measurements were made on samples taken from the section of experimental cable mentioned as having been made before the manufacturing technique was perfected. To obtain an accurate measure of moisture content, groups of tapes were used instead of single tapes. Tests made on a number

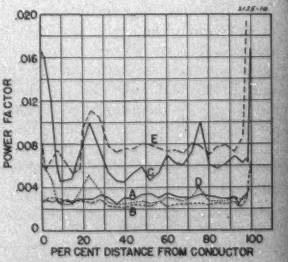


Figure 10. Radial power factor on experimental and commercial cables

A—New cable, "commercial," measured at 80 degrees centigrade

B—Same cable as *A* after 113 days at 100 degrees centigrade

C—New cable, "experimental," measured at 80 degrees centigrade

D—Same cable as *C* measured at 60 degrees centigrade

E—Same cable as *C* after 99 days at 100 degrees centigrade, measured at 80 degrees centigrade

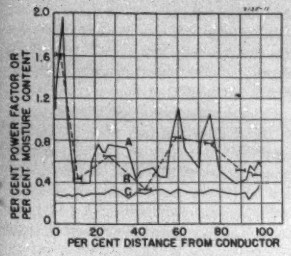


Figure 11. Radial power factor and moisture content of experimental cable

A—Radial power factor on "experimental" cable, measured at 80 degrees centigrade

B—Radial moisture content on "experimental" cable

C—Radial power factor on "commercial" cable, measured at 80 degrees centigrade

of samples show that when the moisture content is below one half of one per cent, it has no significant effect on power factor.

A very noticeable improvement in the 80-degree-centigrade radial power factor took place after the room humidity was maintained below 20 per cent during the taping operations. This improvement is demonstrated by the comparison of the radial power factor curves *A* and *C* shown in Figure 11 for cable made before and after the adoption of humidity control.

Power Factor—Temperature Characteristic

Figure 12 shows a typical power factor versus temperature curve for *SMD* type cable made by the latest practice. This compares very favorably with the best of other types of cable insulation, including that used on oil-filled cable.

Temperature Stability

The temperature stability of the insulation is as important for *SMD* type cable as for other types. The excellent temperature stability of the cable made for commercial use is shown by curves *A* and *B* of Figure 10. Curve *A* shows the radial power factor at 80 degrees centigrade for the new cable, and curve *B* shows the same characteristic on another sample of the same cable after 113 days at 100 degrees centigrade. In both cases the power-factor curve is essentially flat for the full section of the insulation. The aged sample shows no indication of an increase in power factor; in fact, this sample shows a somewhat lower average power factor than the unaged sample. Other samples show no appreciable change in over-all power factor after aging for 162 days at 100 degrees centigrade. Curves *C* and *E* show a similar radial power-factor comparison of "experimental cable," which was manufactured before moisture control was perfected.

Dielectric Strength

The results of dielectric-strength tests on thirteen 30-foot samples taken from the cable made for installation in the commercial line are shown in Figure 13. These samples were tested at a gas pressure of 225 pounds per square inch. There are shown, also, two tests on cable tested at 30 pounds per square inch pressure, one test on cable drained before voltage application, and one test on cable at high temperature. It will be observed that, for tests of a duration between about 1 hour and 100 hours, the approximate life to failure varies inversely as 7.5 power of the

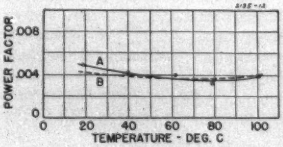


Figure 12. Curves of power factor versus temperature

A—*SMD* type cable "commercial"

B—Typical for oil-filled cable

voltage. There is little or no decrease of strength for periods above 100 hours. For periods less than one hour the strength increases much less rapidly with decreasing time than in the range between 1 and 100 hours. The fact that the dielectric strength for a period of a few hours is reduced no more than about 10 to 20 per cent when tested at 30 pounds per square inch instead of 225 pounds per square inch is rather remarkable. Drainage under very severe conditions, that is, with the cable supported in an inverted U position and maintained at a temperature of 100 degrees centigrade throughout the cross section for a period of 44 days, reduced the strength 10 per cent when tested at a voltage which produced failure in 125 hours. The sample tested hot was held at 75 degrees centigrade by circulating current in the sheath of the cable for about 1,250 hours. Voltage was maintained on it, while hot, for about 530 hours at values increasing from 120 kv to 165 kv. The result of this test was plotted as the equivalent of 108 hours at 160 kv. Even on this basis the test was rather better than the average of the cables tested without heating. It is also to be noted that the power factor at 75 degrees centigrade remained at about 0.3 per cent throughout the test with no tendency to increase.

Figure 8, which shows the power factor versus voltage characteristic, gives a basis for understanding the high long-time strength of this insulation. For a given over-all average stress in the insulation, the actual stresses in the paper and in the oil are lower than in other types of insulation, because of low specific inductive capacity caused by the gas spaces. Thus, as long as there is no breakdown in the gas spaces, it is clear that long-time dielectric strength should be at least as great as for the best of other types of insulation—namely oil-filled insulation. The "ionization" test is one of the best criteria of the beginning of ionization in the gas spaces. It is recognized from extensive tests and engineering experience that the effect of electrical stress in a gas changes sharply and completely at the beginning of ionization (ionization by collision). Above that stress the gas becomes a partial conductor. Even more serious than this is the effect of the bombardment of the solid and liquid insulation at the boundaries of the gas spaces in the gas. This bombardment produces "wax formation," charring of the paper, "coring," and ultimate breakdown. Below the ionization voltage, however, the stress has substantially no effect on the insulation, and, so far as the stress is concerned, the cable should last indefinitely.

A great deal of information has been obtained by dissecting completely (unwinding) the entire length of these many test specimens. In the tests in which complete failure took place after more

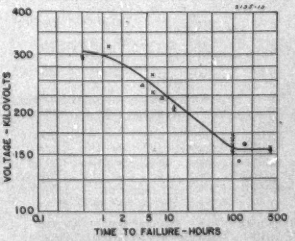


Figure 13. Voltage–time curve

x—Test made at room temperature and 225 pounds per square inch pressure

o—Test made at room temperature and 225 pounds per square inch pressure after the cable had been heated to 100 degrees centigrade in an inverted-U position for 44 days

●—Test made at 75 degrees centigrade and 225 pounds per square inch pressure after 1,250 hours at 75 degrees centigrade

Δ—Tests made at room temperature and 30 pounds per square inch pressure

than 24 hours, there were frequently found one or more partial failures. Because of the small extent of the burning, it was possible to obtain from these partial failures very complete information as to their course. The different partial failures were evidently of similar character but in different stages of development. They originated in the butt space of the tape next to the conductor, usually so close to an edge of the tape as to burn it slightly. When several of these partial failures in different stages were examined, some were found with only a few layers of paper punctured, the size of the hole increasing outwardly from the conductor. In the more advanced stages, the outermost tapes were discolored (brown), usually to a diameter of $^1/_{32}$ inch to $^1/_{16}$ inch, but sometimes to a diameter up to $^1/_8$ inch. In still later stages, "tree design" or "dandrites" appeared at the tip of the advancing puncture. In later stages, these spread radially and outwardly toward final failure. The brown spots were evidently an immediate forerunner of the "tree design," since the first appearance of both occurred when the penetration had reached about five per cent or ten per cent of the total insulation thickness.

Elsewhere than at the complete and partial failures, the insulation seemed only slightly affected by the test. The odor ("mouse-nest odor") which characteristically accompanies insulation tested at high stress was prominent; but no other effects were observed except that on rare occasions traces of wax were found. Several samples were tested after repeated bending produced by rereeling 10 to 15 times around a drum having a diameter of about 16 times the cable diameter. These broke down at 140 kv after durations of 31 to 70 hours. Examination showed that the insulation had been displaced by the handling. This displacement had resulted in regions of wide interturn gaps or valleys between tapes (up to about 0.2 inch as compared with about 0.06 inch before bending) alternating with cross sections where these valleys were practically closed. This characteristic was substantially uniform throughout any cross section. In most of these samples there were several partial failures. All failures and partial failures were in the regions of wide valleys. Most of the cable made for the commercial line was made with slightly smaller valleys and was more resistent to the effect of repeated bending.

Cable handled as severely as required in installation was not affected by the handling. A sample from a length (the leading end of a 1,500-foot length) which had been subjected to excessive pulling strain during installation and had been pulled through about 3,000 feet of pipe, was tested and broke down at about 93 per cent of the voltage of the average new cable.

Table I. Impulse Strength of SMD Type Cable for Various Constructions

Sample No.**	Insulation Thickness (Mils)	No. of Surges	Breakdown Voltage (Kv)	Average Gradient (Volts Per Mil)	Maximum Gradient (Volts Per Mil)	Construction: Paper Tapes No.	Thickness (Mils)	Density*	Saturant Viscosity† or Type
A-1	600	1	680	1,130	1,800	120	5	0.85	3,000
A-2**	600	1	580	965	1,535				
B-1	600	3	900+	1,500+	2,380+	40	3	1.20	1,000
						24	5	0.85	1,000
B-2	600	3	905+	1,510+	2,390+	Balance	5	0.85	3,000
C-1	600	1	610	1,030	1,615	30	2	1.00	Petrolatum
C-2	600	1	715	1,190	1,880	16	3½	1.00	Petrolatum
C-3‡	600	1	520	865	1,375	Balance	5	0.85	3,000
D-1	600	5	900+	1,500+	2,355+				
D-2	600	6	940+	1,565+	2,460+				
D-9	600	3	980+	1,630+	2,560+				
D-11	600	4	925+	1,540+	2,420+				
D-12	600	3	920+	1,530+	2,400+				
D-13	600	3	900+	1,500+	2,355+				
D-14⊗	450	1	820	1,820	2,620	19	2½	1.20	3,000
D-15⊗	450	1	900+	2,000+	2,870+	24	3	1.20	3,000
						Balance	5	0.85	3,000
D-16	450	3	925+	2,055+	2,950+				
D-17⊖	385	1	580	1,505	2,085				
D-18	385	1	720	1,870	2,590				
D-19	385	1	775	2,010	2,790				

Plus values after breakdown voltage indicate that no failure occurred on these samples; on all other samples breakdown occurred in the cable.

Terminal failures occurred in seven additional *D* samples.

200 pounds per square inch nitrogen pressure was applied to each sample for one hour except samples *A*-2 and *C*-3.

** Pressure was applied for 60 hours.

‡ Tested at atmospheric pressure.

⊗ These samples were subjected to abnormal pulling stresses in field before test.

⊖ This sample was subjected to abnormal pulling stresses in field before test and visibly damaged.

* Density of paper tapes is the apparent specific gravity—the volume in cubic centimeters of a tightly wound roll of tape divided by weight in grams.

† Viscosity of saturant is given in Saybolt seconds at 100 degrees centigrade.

Impulse Tests

One of the main questions in connection with the *SMD* type cable was whether or not this cable would have a sufficiently high impulse strength if connected to overhead lines or outdoor substations; therefore, impulse tests were performed on samples of this cable. In this paper samples of cable from the experimental line shall be designated as *A*, and samples of cable subsequently produced, each of different construction, as *B*, *C*, and *D*. The *D* construction was used for the commercial installation.

The results of impulse tests on two *A* samples indicated impulse strengths of 680 and 580 kv. These values were not adequate, because a minimum impulse strength of 750 kv was considered necessary to co-ordinate with the 138-kv-class insulation used for the terminals and other apparatus on the system.

Samples designated as *B* and *C* represent two short experimental lengths on which a limited number of 60-cycle and impulse tests were made. On the first of these, satisfactory values of impulse strength were obtained, but the 60-cycle values were too low, whereas on the second type of construction the 60-cycle values were satisfactory, but the impulse strength was too low. Owing to the limited number of tests, the causes of this could not be determined. This became unimportant, however, as tests on cable with the *D* construction indicated satisfactory values both for 60-cycle and impulse tests. Table I shows the results of these impulse tests.

As the maximum potentials produced by the impulse generator did not cause failure in the cable with the improved construction (*D* samples), the actual impulse strength of such cables could not be determined. Breakdowns were obtained, however, on samples on which insulation thickness was reduced by removing a number of tapes from the outside of the insulation. The results of these tests

are shown in Table I, samples *D*-14 to 19 inclusive. Two reduced insulation thicknesses were selected, so that breakdown voltage values could be conveniently compared with those obtained on other types of cables previously tested.

Figures 14 and 15 graphically illustrate the breakdown voltage values and maximum voltage gradients, respectively, of the samples tabulated in Table I, and compared with the results of previous tests by one of the authors[4] and others,[5,6] on the basis of equal insulation thicknesses. The slanting line on Figure 14 connects minimum breakdown values obtained by the authors and others on oil-

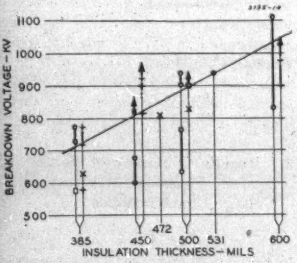


Figure 14. Impulse strength of *SMD* type cable

o—Oil-filled
□—Compression and Oilostatic
X—Solid
+—*SMD*

filled, compression, Oilostatic, solid, and *SMD* cables, having insulation thicknesses of 385, 450, and 500 mils, respectively. These lines were extended to the full insulation thickness range for the *D* samples, in order to obtain an indication of the impulse strength which otherwise was not obtainable, because of the 1,000-kv limitation of the impulse generator.

From Figures 14 and 15 it is evident that on the basis of *average stress* the *SMD* type cable in the commercial line has an impulse strength as high as has been obtained by various observers for well-made oil-filled cable of standard construction and equal insulation thickness. On the basis of *maximum stress* as customarily calculated, without taking into account the effect of stranding, the impulse strength of the conductor-shielded *SMD* type cable is higher than that of unshielded oil-filled cable. It is thought that the conductor shielding of the *SMD* type cable is responsible for this difference, although the extent of the benefit from this shielding has not been directly determined.

With 600 mils of insulation the impulse strength of the *SMD* cable is in excess of 1,000 kv. These tests indicate that 400 to 425 mils of insulation should be adequate for the desired impulse strength of 750 kv.

Summary

1. Nonleaded high-pressure gas-filled cable can be installed in a steel pipe without the insulation being adversely affected due to atmospheric exposure or mechanical handling.

2. No difficulty was encountered in the installation of 1,500-foot section lengths of cable on the commercial line. Based on the relatively low pulling stresses (7,200 pounds maximum), it appears perfectly feasible to install this type cable in lengths up to 2,000 feet.

3. The use of paper, preimpregnated with viscous compound, prevents migration at normal operating temperatures and allows installation on steep grades or in vertical runs without stop joints or other devices.

4. The satisfactory results on this type of cable are due in part to the development and use of a saturant of high viscosity and of excellent electrical properties.

5. The 60-cycle dielectric strength, both short- and long-time, is equivalent to that of oil-filled cable.

6. The impulse strength is at least the equal of oil-filled cable.

7. Power-factor values are approximately constant over a temperature range of 20 to 100 degrees centigrade.

8. The power factor was not affected even after six months at a temperature of 100 degrees centigrade.

9. The radial power-factor curve is flat even at 80 degrees centigrade, where impurities often cause erratic results.

10. Great uniformity of the insulation is indicated by the fact that on long-time voltage tests there are normally numerous partial failures, in addition to the completed failure.

11. The same insulation thicknesses as used on oil-filled cable can be used on high-pressure gas-filled cable, and all oil-fill cable tests met with a gas pressure of 30 pounds per square inch on reel lengths and 225 pounds per square inch on samples.

12. High-pressure gas-filled cable is practical for handling loads of the order of 100,000 kva and above.

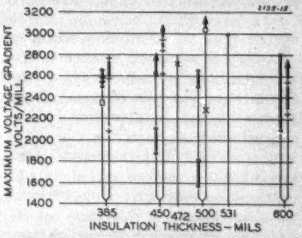


Figure 15. Maximum stress values for the impulse measurements shown on Figure 14

No correction made for the effect of stranding on maximum stress
o—Oil-filled
□—Compression and Oilostatic
X—Solid
+—*SMD*

13. Measured values of thermal resistivity are given for several kinds of soil.

14. High-pressure gas-filled cable with preimpregnated paper can be manufactured on standard equipment, with only minor changes, provided humidity is maintained below 20 per cent.

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Transient Recovery-Voltage Characteristics of Electric-Power Systems

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1. Introduction

THE existence of transient recovery-voltage phenomena in connection with the interruption of short circuits by circuit breakers has been recognized for a number of years, and from time to time measurements and calculations have been made on actual field circuits.[2,5] However, while these more or less isolated and scattered instances have provided some valuable information, they have not afforded a comprehensive picture of transient-recovery voltage conditions existing in the field.

In order to provide the electric-power industry with a better understanding of and more complete data on transient recovery-voltage conditions, and, perhaps more particularly, to provide such data as a guide to the circuit-breaker designers, a field survey of several representative electric-power systems was recently carried out under the sponsorship of the committee on electric switching and switchgear of the Association of Edison Illuminating Companies. By permission of that organization and the participating electric power companies, some of the outstanding results and conclusions from this survey were made available to the AIEE committee on protective devices for presentation in this paper.

2. Transient Recovery Voltage—Theory and Definitions

While a number of excellent papers covering this phenomenon have been published in the literature,[1-6] a brief review is believed to be in order here.

The term recovery voltage applied to a circuit breaker refers to the voltage established across the open contacts after the arc is extinguished. The initial or transient recovery voltage is produced by a sudden change in circuit conditions, and its characteristics are determined by circuit constants. The normal-frequency recovery voltage is the generated system voltage finally maintained across the open contacts after the transient voltages have disappeared.

Since short-circuit currents are generally limited principally by reactance, it follows that the current is nearly 90 degrees out of phase with the voltage. Consequently, at the point of arc interruption, normally on or near the zero point of the current wave, the generated voltage is close to its maximum peak value. The voltage at the breaker, of course, prior to interruption, is held down to zero or nearly zero by the short circuit, but upon arc interruption attempts to recover immediately to the peak value of the wave. It is prevented from doing so instantaneously, however, by the effective capacitance across the breaker contacts, and there results instead a transient recovery-voltage oscillation. The frequency of this oscillation is determined by the inductance and capacitance of the circuit; the amplitude may reach double the normal-frequency crest voltage. In general, the combination of lumped reactance in the circuit between breaker and power source, with low capacitance-to-ground in the circuit between breaker and reactance, gives rise to the highest oscillating frequencies.

The severity of a given circuit is commonly characterized by the *rate of rise of transient recovery voltage*, which is determined by drawing a line from the zero point of the oscillating voltage wave, either to the peak of the first loop of the transient voltage oscillation, or as a tangent to the first voltage loop. This simple procedure, however, is not always adequate. The circuits involved are generally somewhat complex, so that the *transient recovery-voltage characteristics* are usually compounded of two or more superimposed oscillating frequencies. If, as occasionally happens, the first high-frequency loop has a smaller amplitude than a succeeding lower-frequency crest, the significance of rate of rise based upon the higher frequency but lower amplitude oscillation, may be decidedly questionable and subject to arbitrary judgment.

To avoid this difficulty, the complete transient recovery-voltage characteristic of a circuit should be determined. This characteristic, modified by circuit-breaker and test factors as described below, may be obtained directly from oscillograms taken in short-circuit tests, or it may be calculated from the constants of the circuit. In the AEIC survey of electric-power systems mentioned above, circuit characteristics were calculated in this manner, and the results were obtained in terms of an envelope of the transient recovery-voltage characteristics, composed of two and sometimes three major frequency components. In order to bring the task of calculating such characteristics within feasible limits in terms of manhours of work required, certain approximations and simplifying assumptions were necessarily employed. A complete description of this simplified method of calculation, including the limits of accuracy obtained, is given in a companion paper.[7]

3. Results of Survey of Power-System Transient Recovery-Voltage Characteristics

The survey, which was made entirely by calculations except for direct measurements of a few circuit capacitances, was carried out on the systems of six power companies, selected as representing both concentrated urban types and distributed types of systems. Practically all of the circuit-breaker locations on these six systems were covered either by actual calculations or by a comparative estimating procedure. Where the system connections varied somewhat with different operating setups, and also where the assumed location of the fault affected the severity of the recovery-voltage characteristics, the calculations were made on the basis of the conditions which would give the most severe characteristics. With these results on the six systems covered by the survey, it was felt that a sufficient cross section had been obtained to draw general conclusions as to the transient recovery-voltage conditions existing throughout the industry.

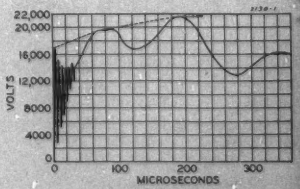

Figure 1. Typical recovery-voltage envelope and oscillating characteristic

Paper 42-130, recommended by the AIEE committee on protective devices for presentation at the AIEE summer convention, Chicago, Ill., June 22-26, 1942. Manuscript submitted May 4, 1942; made available for printing May 21, 1942.

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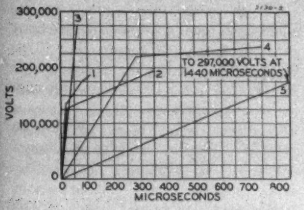


Figure 2. Representative envelopes of transient recovery voltage for 120,000- to 132,000-volt systems

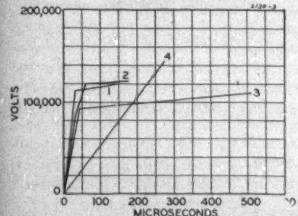


Figure 3. Representative envelopes of transient recovery voltage for 69,000-volt systems

As stated above, the survey was carried out on the basis of determining the envelope of the recovery-voltage characteristic, rather than on the basis of a simple rate of rise of transient recovery voltage. A typical recovery-voltage envelope, together with the complete oscillating characteristic from which it was drawn, is shown in Figure 1. Also groups of typical recovery-voltage envelopes, shown in Figures 2 to 6 inclusive, were chosen as illustrations from each of the following voltage classifications:

120,000- to	132,000-volt systems
	69,000-volt systems
22,000- to	34,500-volt systems
11,000- to	13,800-volt systems
4,000- to	4,800-volt systems

For practical purposes, the envelope is sufficient to define the transient recovery-voltage characteristic, since it gives the magnitude of the first peak and the maximum peak, as well as any intermediate peaks found to be significant. Only the first peak and the maximum peak were recorded when the intermediate peaks were found to be less in amplitude than a corresponding point in time on the envelope connecting the first peak and the maximum peak. In other words, an intermediate peak was included if it raised the envelope, but not if it caused the envelope to drop below a straight line drawn between the first and maximum peaks. Also the envelopes were not extended beyond the point of maximum peak.

An analysis of the recovery-voltage curves shown in Figure 2 indicates a wide range of rates of rise for the various curves. Based on the first peak, curve 1 shows a rate of 8,300 volts per microsecond, while curve 5 shows only 210 volts per microsecond. The higher rates shown in curves 1 to 3 were obtained in connection with breaker locations where the fault was limited by a transformer fairly near the breaker, whereas the lower rates of curves 4 and 5 resulted from locations where there was no large lumped reactance in the circuit close to the breaker. Further examination of curve 1 shows that the first peak, which is 71 per cent of the final peak, occurs in 16 microseconds, the second peak in 80 microseconds, while the final and maximum peak is reached at 110 microseconds. Curves 2 and 4 show only

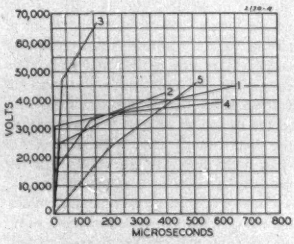


Figure 4. Representative envelopes of transient recovery voltage for 22,000- to 34,500-volt systems

two peaks, while curves 3 and 5 reach maximum values without any significant intermediate peaks. Figures 3, 4, and 6 in like manner show various typical characteristics for their respective voltage classes.

The envelopes shown in Figure 5 have been drawn in two ways:

1. With a scale going to 1,000 microseconds in order to include the complete characteristic.

2. With a scale of only ten microseconds in order to show the relatively high-speed transients in greater detail.

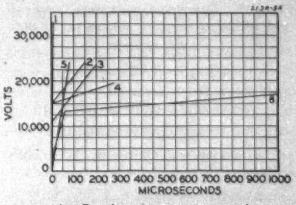
Complete numerical results of the survey were tabulated in terms of the information given on the envelope, that is, in terms of two or three significant peaks, and the time in microseconds required to reach each of these peaks. While these tabulations are not reproduced in this paper, the net results of the survey, in terms of rate of rise of transient recovery voltage, are given graphically in the form of cumulative percentage curves, shown in Figures 7 to 11 inclusive. The rate of rise used in these curves is based upon the first peak of the recovery characteristic, except in cases where this peak was found to be of abnormally low magnitude compared with later peaks.

The abscissae of these curves show the percentage of breaker locations where the rate of rise exceeds the value given by the ordinate. For example, referring to Figure 7, only 15 per cent of the breaker locations may be subjected to rates of rise of 5,000 volts per microsecond or higher. Also, it will be noted that 53 per cent of the breakers are located where the rate of rise does not exceed 1,000 volts per microsecond; the remainder of the breaker locations, or 32 per cent being subjected to rates of rise between 1,000 and 5,000 volts per microsecond.

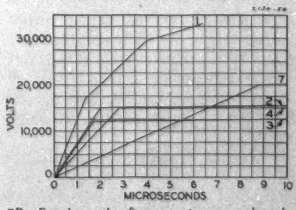
All of these results, of course, are given in terms of the characteristic of the circuits themselves and do not take into account the various factors which tend to modify the severity of the recovery-voltage characteristics actually obtained on a breaker. These factors include:

(*a*). Asymmetry of the current wave.

(*b*). Decay of flux in generators during short circuit.



5A—Envelopes to maximum peak



5B—Envelopes for first ten microseconds only

Figure 5. Representative envelopes of transient recovery voltage for 11,000- to 13,800-volt systems

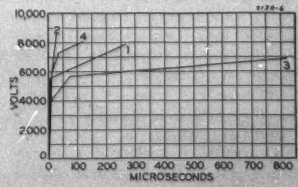


Figure 6. Representative envelopes of transient recovery voltage for 4,000- to 4,800-volt systems

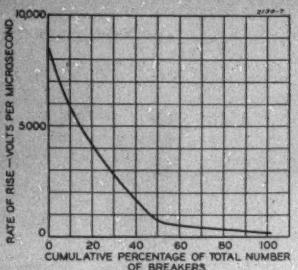


Figure 7. Cumulative percentage curves of rates of rise of recovery voltage for 120,000- to 132,000-volt systems

(Based on 345 breakers)

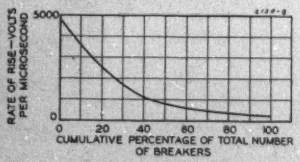


Figure 8. Cumulative percentage curves of rates of rise of recovery voltage for 69,000-volt systems

(Based on 342 breakers)

(*c*). Arc-voltage drop in the fault.

(*d*). Arc-voltage drop in the breaker.

(*e*). Conduction of current in the breaker after current zero.

In general, the above factors tend to reduce the severity of the recovery-voltage characteristic. On an actual circuit-breaker test, it is usually possible to account for the effect of these various factors by analyzing oscillograms of recovery voltage taken on the test and thereby to obtain a check on the calculated values.

The results of the survey, as summarized in Figures 7 to 11 inclusive, have shown that some of the calculated circuit recovery-voltage rates are substantially higher than the maximum rates disclosed by previous scattered information on this subject. Also the results show that the occurrence of high values of circuit recovery-voltage rates (on the order of 5,000 to 8,000 volts per microsecond) is considerably more widespread than had previously been suspected.

4. Significance of Results and Conclusions

In appraising the significance of these results, it is necessary first of all to take into account the modification of the maximum rate of rise of recovery voltage which is brought about in actual circuit-breaker operation. The data presented in a companion paper indicate the possibility that, for certain types of breakers at least, the effect of the breaker in reducing the severity of these transients increases as the calculated circuit values increase. Therefore, this may limit the actual rate of rise which a circuit can impress across the contacts of a breaker, regardless of the constants of the circuit. If this effect is rather general for breakers now in service, it may constitute one of the reasons why few outstanding instances of extreme rates of rise causing difficulty in the operation of circuit breakers have been recorded.

As to the significance of these results to circuit-breaker users, particularly in the operation of the great number of breakers already in service, and in view of the greater prevalence of fairly high rates of rise of recovery voltage than previously suspected, it may be said that there have been some but only a few instances recorded where circuit breakers were subjected to greater distress while interrupting short circuits under high rates of rise than under low rate conditions. In the group of systems covered by this survey, a study of operating records failed to disclose a systematic correlation between recovery rates and breaker distress or failures. Such effects as undoubtedly do exist would be evidenced in increased arc lengths and some additional maintenance due to increased burning and other phenomena. Experience seems to show in general, however, that circuit breakers have been designed with sufficient stroke to take care of even the highest rates of rise of recovery voltage, so that cases of breaker trouble directly attributable to recovery rates have been very rare.

On the other hand, it is believed that the results of the survey will be of major significance and importance in connection with the design and manufacture of circuit breakers. Important elements in the design, such as length of stroke and similar considerations, are determined to a large extent by rate of rise of recovery voltage. Therefore, while it may fortunately be true that liberal design allowances, combined with circuit-breaker modifying effects, have in the past produced breakers capable of withstanding the severe transient recovery-voltage conditions that are now known to exist, it may be more important in the future, particularly in connection with the development of radically new designs of circuit breakers, to have available a true picture of recovery-voltage requirements. It is believed that the results of the survey

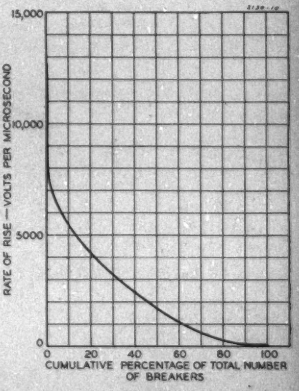


Figure 10. Cumulative percentage curves of rates of rise of recovery voltage for 11,000- to 13,800-volt systems

(Based on 2,250 breakers)

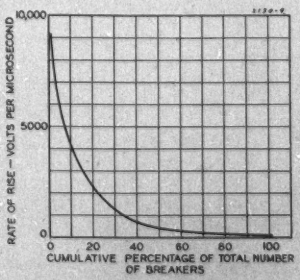


Figure 9. Cumulative percentage curves of rates of rise of recovery voltage for 22,000- to 34,500-volt systems

(Based on 1,975 breakers)

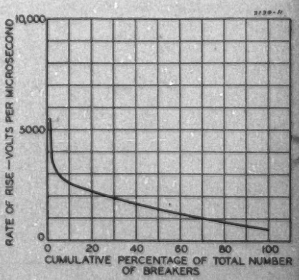


Figure 11. Cumulative percentage curves of rates of rise of recovery voltage for 4,000- to 4,800-volt systems

(Based on 3,975 breakers)

Emergency Overloads for Oil-Insulated Transformers

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IN periods of high industrial activity transformer loads are generally high, and it is essential that operators know what overloads they can carry safely in emergencies. In order to do this effectively, it is necessary to know what temperatures will be reached after various overloads for different durations of time and the effects of temperature and time on the dielectric and mechanical strength of the insulation. If limitations between these things and the degree of insulation deterioration can be established, it is possible to make recommendations for safe overload times and temperatures.

In Part I of this paper some new data are presented on the effect of temperatures and oil acidity on the insulation, and some recommendations for maximum temperatures and their duration are made. This paper differs from previous studies on this subject in that definite evaluation of the effect of acidity on the insulation strength is given. Acids are formed in service by contact between oxygen and transformer oil. Excluding this contact by blanketing the transformer with inert gas results in a high mechanical strength of the insulation at a given temperature and time, or, conversely, permits a high operating temperature for a given loss in life. In considering this paper, it should be borne in mind that the data refer to the mechanical strength of the insulation only. Neither the 60-cycle nor the impulse dielectric strength are affected to any extent by the conditions of test. The true criterion of insulation deterioration therefore is not mechanical strength alone, but the dielectric strength must be given due consideration. Experience has shown that satisfactory operation can be obtained with much reduced mechanical strength.

Even after the recommendations for temperatures and time duration for insulation are made, it is necessary to know the overloads and times which will give corresponding temperatures. Various sizes and types of transformers vary widely in this respect. Some transformers which are well ventilated may have low gradients and correspondingly high overload capacities; most of the larger power transformers come within this class. Smaller transformers are wound with small wire with many turns in a single coil. They will normally have much higher gradients between copper and oil and correspondingly lower overload capacities. In Part II the characteristics of these various types of transformers are given along with recommendations for safe emergency overloads for given time and temperature limits.

Paper 42-101, recommended by the AIEE committee on electrical machinery for presentation at the AIEE summer convention, Chicago, Ill., June 22-26, 1942. Manuscript submitted April 10, 1942; made available for printing May 14, 1942.

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Part I. Effect of Temperature on Cellulose Insulation

The life of cellulose insulation is decidedly influenced by three factors, namely, temperature, contact with oxygen, and exposure to acidity. Doctor C. F. Hill[1] has shown that cellulose insulation is stable for long periods of time below 90 to 95 degrees centigrade, when protected by an inert atmosphere. Doctor F. M. Clark[2] has classified the mechanical deterioration of cellulose as being caused by oxidation, pyrochemical changes, or both.

The object of this paper is to give additional evidence in regard to the rate of deterioration of cellulose insulation and to show that transformers can be exposed to short-time overloads even at high temperatures without damaging the mechanical strength of the insulation to a great extent.

Figure 1 shows the decrease in tensile strength of Manila paper when sealed at atmospheric pressure in an oxygen-free atmosphere. It is interesting to note the rapid decrease in tensile strength which takes place at 135 degrees centigrade. This occurs when temperatures are maintained at which thermal decomposition takes place. At 120 degrees centigrade, the tensile strength drops to approximately 50 per cent and levels off. It would appear that this 50 per cent strength would be maintained for long periods of time. Figure 2 shows the change in acidity of oil with Manila paper in oxygen-free oil protected by a nitrogen atmosphere. One of the main products of thermal decomposition is the formation of acid which forms a catalyst for further decomposition. The inert atmosphere prevents the formation of acid product at 120 degrees centigrade and below, showing the decided advantage of protecting the oil of a transformer against exposure to air.

The same data for Figure 1 are used to produce Figure 3. The remaining tensile strength of Manila paper after exposure to different temperatures in oxygen-free oil for different periods of time is plotted in this figure with temperature and time as ordinate + abscissae. These curves are of special interest to both the designer and the operator of transformers, because they can be used to predict the amount of mechanical damage done to transformer insulation after it has been operated at given temperatures for specified lengths of time. For example, if not less than 50 per cent mechanical strength is required at all times, it is interesting to see that the total period of operation at 140 degrees centigrade should be not

will have their greatest value in providing this information.

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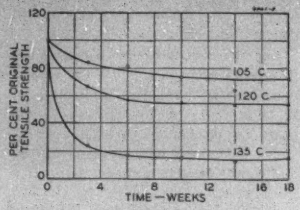

Figure 1.. Decrease in tensile strength of Manila paper in oxygen-free oil protected by a nitrogen atmosphere

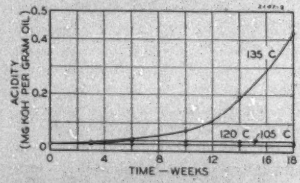

Figure 2. Change in acidity of oil with Manila paper in oxygen-free oil protected by a nitrogen atmosphere

more than two days, because in this time the *cellulose* has decreased in tensile strength to 50 per cent. However, with overloads at which the temperature reached only 135 degrees centigrade, a total of five days would be possible. If 40 per cent of the original mechanical strength is the lowest desired, a total of nine days at a temperature of 135 degrees centigrade may be allowed.

Figure 4 is a plot of the lowest tensile strength for paper insulation after 18 weeks under oxygen-free oil at various temperatures. From this figure one can select the temperature for transformer operation when the ultimate tensile strength has been selected. For example, if not less than 60 per cent of the original strength is required, the operating temperature should never be more than 115 degrees centigrade.

Based on the above data, the following practical conclusion might be drawn. The load which may be carried in the operation of a transformer is governed by the desired life of the transformer. From the experimental data presented here it is felt that an oil-insulated transformer may be operated at temperatures up to 120 degrees centigrade continuously, and even above, during short-time overloads, without seriously damaging the insulating materials, provided an inert (oxygen-free) atmosphere is maintained in contact with the oil at all times, and provided the acidity of the oil in contact with the insulating materials is maintained at a low value. Below 120 degrees centigrade the main deterioration in mechanical strength is caused by oxidation, while above this temperature the thermal decomposition of the cellulose is very detrimental. The thermal change results in the formation of gases, water, and other decomposition products. Oxidation, which takes place below 120 degrees centigrade, is eliminated to a very large extent by the use of an inert atmosphere.

Figure 5 shows the decrease of tensile strength of Fuller board when included with a varnished cotton tape in oxygen-free oil protected by a nitrogen atmosphere and at atmospheric pressure. It is quite interesting to compare this curve with Figure 1. At 135 degrees centigrade, the rate of decrease in tensile strength is quite similar to that of paper with no acids present other than those from decomposition. The decided effect of the acidity can be seen at 120 and 105 degrees centigrade. At 120 degrees centigrade,

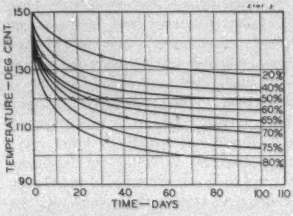

Figure 3. Percentage of initial tensile strength reached by Manila-paper insulation in oxygen-free oil protected by a nitrogen atmosphere

the final tensile strength is less than twenty per cent as compared with 54 per cent with no acids present; and for 105 degrees centigrade, 44 per cent as compared with 72 per cent. It would appear from these comparisons that it is of utmost importance to maintain low acidity and to avoid acid-forming materials in the construction.

The acidity in contact with the Fuller board samples from the varnished cloth is shown in Figure 6. While these acidities are higher than those of usable transformer oil, it simulates the effect of lower acidities over longer periods of time.

The data for Figure 3 are used again to produce Figure 7. The curves show the part of the initial tensile strength remaining at the end of various periods versus temperature. If we choose 50 per cent as the minimum mechanical strength required, this would be reached in 1.5 days compared with two days from Figure 3. Likewise, at 135 degrees centigrade, the insulation would have reached 50 per cent strength in three days. For 40 per cent strength the total time of overloads could be seven days, compared with nine days with low acidity. A significant difference between this figure and Figure 3 is that the tensile strength continues to decrease even after 100 days, while in the low-acidity oil the decrease in tensile strength shows a greater tendency to reach a constant value for a given temperature.

Figure 8 shows the lowest tensile strength for Fuller board insulation after 18 weeks of exposure to high-acidity oil. If we choose 50 per cent as the minimum required tensile strength, the operating temperature should not be more than 100 degrees centigrade. However, this is for a period of only 18 weeks and since the tensile strength continues to decrease, due to the presence of acids, it would indicate a still lower temperature.

The curves of Figures 5 and 8 show that the presence of acids in contact with cellulose insulation seriously catalyzes not only oxidation changes but also thermal decomposition. Care should be taken to maintain low-acidity oil in order to obtain the longest life from the cellulose insulation. Varnishes and varnished tapes have been a source of acids in transformers. The use of synthetic materials in place of natural varnishes in modern transformer construction has practically eliminated this source of acids.

Figure 9 shows the similarity in behavior between Fuller board and paper insulation. The Fuller board was in contact with oxygen-free oil under the same conditions as for Figure 1. While the Fuller board is some better at 105 and 120 degrees centigrade, it is interesting to note that at 135 degrees, thermal decomposition destroys most of the tensile strength.

Figure 10 shows the rate of increase in acidity of oil samples with the same materials as for Figure 6, except that the oil has free access to the oxygen of the air. Here the acidity shows a decided increase in 18 weeks, much greater than in Figure 2. Comparison of these figures shows that to obtain full advantage of preserva-

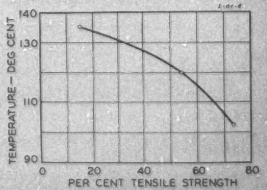

Figure 4. Lowest tensile strength for paper insulation after 18 weeks under oxygen-free oil protected by a nitrogen atmosphere

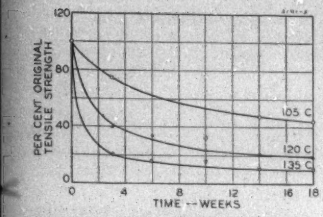

Figure 5. Decrease in tensile strength of Fuller board, together with varnished cloth, in oxygen-free oil protected by a nitrogen atmosphere

tive measures in transformers, no acid-forming varnishes or treatments should be used.

Figure 11 shows test data taken on paper in transformer oil at various temperatures with the samples open to the air. Comparison of these curves with Figure 1 shows the great benefit obtained by protecting the samples from oxygen, particularly at temperatures of 120 degrees centigrade and less.

It is possible from the data given above to make recommendations for short-time emergency overload temperatures of transformers based on given amounts of decrease in mechanical strength of the insulation. One set of values that has been proposed is given in Table A.

Inspection of these values will show that if a given temperature from the table were reached 20 times for the time specified, the insulation would have a tensile strength of approximately 80 per cent of its original value. If emergency overloads of the same character as described in the table were to be applied once a year for 20 years, we would, therefore, not expect that the insulation would be appreciably lower than 80 per cent of its original value. Figure 3 is used in reaching this conclusion. This assumes that there was no deterioration due to steady operation. It would be more practical, however, to consider that the transformer might reach 105 degrees hot-spot temperature for considerable durations of time, and, if this were true, its mechanical strength would be somewhere between 80 and 75 per cent of its original value. If the emergency operations were to take place after this initial deterioration, a method of estimating its ultimate deterioration is as follows:

Suppose we were to consider that there would be 20 overloads for 24 hours which would reach 115 degrees; then the deterioration due to the steady load would be equivalent to approximately 24 days at 115 degrees without the deterioration due to the overload. The additional 20 days would then be equivalent to 44 total days at 115 degrees, which would result in approximately 65 per cent of the original mechanical strength of the insulation. Similar methods of calculation could be used for any of the other emergency overload temperatures. If an operator desired to determine the amount of deterioration under other conditions of loading and time, the curve data provide an easy graphical method for making such an estimate.

It is believed that the decrease in mechanical strength resulting from Table A is reasonable and safe for general use. The ultimate strength requirements depend upon many factors determined by service conditions. The severity and frequency of short circuits is an important factor, as well as whether or not the apparatus remains fixed or is to be transported. Since the dielectric strength remains practically unchanged, a reduction of 40 to 50 per cent in the mechanical strength of the insulation over a 20-year period would not be considered excessive for normal operating requirements.

Summary

New data on the rate of deterioration of cellulose insulation at different temperatures have been obtained. From them a table of time periods and temperatures has been made at which oil-insulated transformers may be operated in order that specific cellulose insulation strengths of approximately 65 per cent of the original value may be maintained. It is expected that this value will be maintained even after operation of a considerable length of time at 105 degrees centigrade.

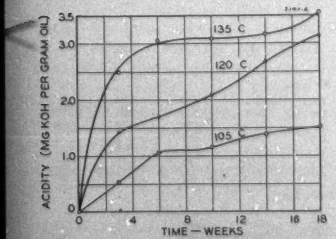

Figure 6. Change in acidity with Fuller board and varnished cloth under oxygen-free oil protected by a nitrogen atmosphere

Table A. Duration of Overload Ultimate Temperatures

Hours	Degrees
1/4	145
1/2	140
1	135
2	130
4	125
8	120
24	115

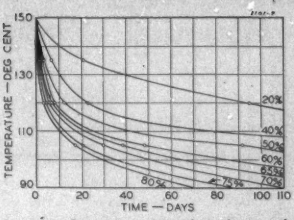

Figure 7. Percentage of initial tensile strength reached by Fuller board, together with varnished cloth, in oxygen-free oil protected by a nitrogen atmosphere

Part II. Recommended Emergency Overloads for Transformers

After Table A in Part I has been established, it is still necessary to correlate the data with overloads which will result in these temperatures after given lengths of time. In order to do this, it is necessary to know what the characteristics of average transformers are, both in respect to the gradient between the insulation and the oil, and the length of time which it takes for the oil to reach given temperatures under given load conditions. Data may be found in several places for estimating the gradients between oil and insulation and also the rate of oil rise during transformer overloads. One such reference is a recent paper on "Hot-Spot Temperatures in Transformers."[3] Before these data can be used, however, it is desirable to establish available characteristics for several sizes of transformers.

It is suggested that seven classes of

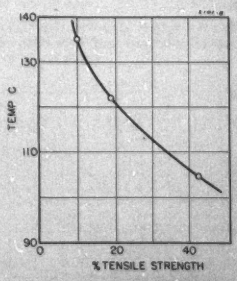

Figure 8. Lowest tensile strength of Fuller board, together with varnished cloth, after 18 weeks in oxygen-free oil protected by a nitrogen atmosphere

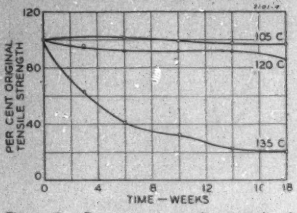

Figure 9. Decrease in tensile strength of Fuller board in oxygen-free oil, protected by a nitrogen atmosphere

transformers be considered. These classes may be described as follows:

Class 1. Many transformers use round wire, and there is a considerable gradient between the center of such coils and the oil. There are also some ribbon-wound coils, which have several layers and several turns per layer. We suggest that this class include transformers up to 150 kva, 25 kv, and transformers with windings of all voltage classes rated at 15 amperes or less. This class is to be oil-insulated, self-cooled.

Class 2. The next larger transformers than those described in class 1 generally have strap windings with at least one side or edge of each conductor exposed to oil. Surely, up to 69 kv such transformers would not have heavy conductor insulation; therefore, this class is limited to power and distribution transformers up to 69 kv, oil-insulated, self-cooled.

Class 3. This class is similar to class 2 except that it is for forced air-cooled transformers.

Class 4. Some transformers include regulating equipment and are used as unit substations. Such transformers are very similar to the ordinary self-cooled transformer with the exception that the tank is larger, and there is much more oil used than in the ordinary self-cooled transformer. The result is that the transformer has a longer time constant than the ordinary self-cooled transformer. It is suggested, therefore, that class 4 include transformers such as unit substation transformers and be similar to class 2 except for longer time constants.

Class 5. It is suggested that this class include oil-insulated unit substation transformers, which are cooled with forced air. This class is then the same as class 3, except that the transformers have longer time constants.

Class 6. Large high-voltage power transformers may require heavier insulation on the conductors than smaller transformers. This, in turn, will result in higher gradients between the copper and the oil. Therefore, slightly different characteristics should be used for these transformers than for smaller units exemplified in class 2; class 6 should be approximately the same as class 2 except for higher gradients.

Class 7. It is suggested that class 7 correspond to class 6 except that the transformers have forced air-cooled ratings.

A tabulation of the proposed characteristics of these various classes is given in Table I, and it might be well to describe how the various values were obtained. For example, in class 1 the designer can calculate the watts per square inch of losses transmitted from the coil surface to the oil. From this, he can make an approximate estimate of the gradient between the coil and the oil, based on designs in common use. For class 1 this gradient should be in the order of and not exceeding 20 degrees centigrade at normal load. Likewise, the top oil rise is in the order of 40 degrees for such transformers. The difference between average oil and top oil is in the order of five degrees. The loss ratio refers to the ratio of the copper loss to the iron loss at rated load, and this loss ratio approaches limits now commonly used. Time constants are given in hours. These values are average values for transformers of the ratings referred to above.

In a previous paper[3] a method was indicated for calculating transformer hot-spot temperatures. In this paper it was shown that changes in viscosity tend to decrease gradients at high oil temperatures. These decreases further tend to counteract increases in gradients due to losses. Therefore, no great error should result if the change in copper resistance were ignored. This is not exactly true but probably is within reasonable error, considering that average characteristics of transformers are being considered. On this basis, it would be reasonable to assume that the gradient between the copper and oil varies approximately as the 0.8 power of the copper losses, which, in turn, are assumed to vary as the square of the load.

In the paper[3] previously mentioned, a method was shown for calculating oil temperatures after short-time loads. Cal-

Table I. Suggested Classes for Transformers for Calculating Emergency Overloads

	Class						
	1	2	3	4	5	6	7
Hot-spot rise	60°	60°	63°	60°	63°	62°	65°
Top-oil rise	40°	50°	47°	50°	47°	50°	46°
Loss ratio	2.5:1	2.5:1	4.5:1	2.5:1	4.5:1	2.5:1	4.5:1
Time constant	3	4	2.5	6	4	4	2.5

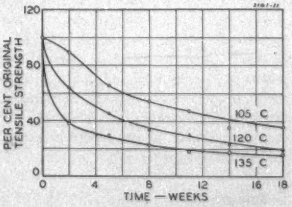

Figure 11. Decrease in tensile strength of Manila paper under oil exposed to air

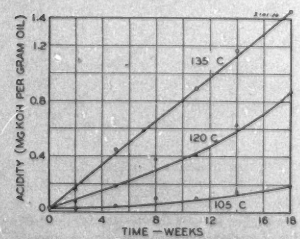

Figure 10. Change in acidity with Fuller board under oil exposed to air

Table II. Emergency Short-Time Overloads (Per Cent of Rated Load)

Time (Hr.)	Temperature	Class 1	2	3	4	5	6	7
		Following No Load						
1/4	145	253	360	291	372	288	333	252
1/2	140	230	320	248	334	259	289	229
1	135	203	265	210	295	230	249	196
2	130	180	215	172	239	188	202	166
4	125	155	170	145	193	157	167	143
8	120	138	145	128	158	135	141	127
24	115	130	130	123	132	124	128	121
		Following Full Load						
1/4	145	215	280	225	296	230	271	206
1/2	140	197	255	205	265	208	238	187
1	135	180	218	183	234	185	205	166
2	130	163	185	155	198	160	174	149
4	125	148	155	140	169	140	151	135
8	120	135	138	128	147	131	138	128
24	115	130	130	123	132	124	128	121

culations were made on the basis of average oil temperatures, and an approximate constant value added to them. The method in common use before was to calculate the top oil temperatures directly. Comparative calculations show that there is no great difference between the two methods of calculation. For the purpose of simplicity and also for greater conservatism, it is intended to use the older and simpler method in this paper.

For example, suppose we take class 1 and calculate the overload, which can be carried for eight hours to reach a temperature of 120 degrees centigrade, at an ambient temperature of 30, following full load. As shown in the preceding paper, it is easiest to use "cut and try" methods, and a value of 135 per cent load can be assumed as a basis. At 135 per cent load the copper losses will be 1.82 times as great as at full load. If the total losses at full load in the first case were 3.5 times the iron loss, in the second case it would be 5.55 times the iron loss. If the top oil rise were 40 degrees in the first case, it would be ultimately, $\frac{(5.55)^{0.8}}{(3.5)} \times 40$ degrees or approximately 58 degrees centigrade. The change in load from full load to 135 per cent results in an ultimate change in oil temperature of 18 degrees. This change will not be entirely completed in eight hours, and the rise which will result in that time will be:

T_8 hr $= 18(1-e^{-8/4}) =$ approximately 17 degrees

This means that the oil rise after eight hours will be 57 degrees.

The gradient at full load is given as 20 degrees. At 135 per cent load the copper loss is 1.82 times the value at full load, and the gradient should be $1.82^{0.8}$ or 1.6 times as great as the gradient at full load. 1.6×20 degrees is 32 degrees. The total temperature would be the sum of the ambient temperature, 30 degrees, plus the gradient between air and top oil, 57 degrees, plus the gradient between oil and copper, 32 degrees, or a total of 119 degrees centigrade. Since this temperature is slightly below the 120 degrees allowed, this percentage was considered sufficiently accurate for use in Table II.

It will be seen upon inspection of Table II that the proposed overloads are much higher than those previously recommended for use in the American Standards Association Guides for Operation for Transformers. This occurs, partly because the original guides did not differentiate between different types of transformers, and partly because temperature rises which were permitted were lower than those proposed in Part I of this paper. Still another reason is that the number of emergencies was not specifically limited, and in the present paper 20 are assumed, on the basis of 20-year life and one emergency per year on the average. It is felt that sufficient information is given in this paper to permit the operator to use judgment and discretion in specifying safe overloads for his application.

A New Jewel for Indicating Instruments

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IT has been almost universal practice to use highly polished sapphire jewel bearings, cut approximately in the form shown by Figure 1a, in electric indicating instruments. Such a jewel is commonly known as a "Vee." The other member of the bearing is a cone-shaped piece of hardened steel or other hard metal also accurately cut and highly polished. Figures 2 and 3 show both the common proportions of these parts and the clearances involved. Figure 2 shows an instrument which has the moving shaft vertical, and Figure 3 an instrument with the moving shaft horizontal. Figure 4a shows typical moving systems and jewel settings.

The making of sapphire Vees is a very highly specialized art, and the great majority of machine equipment and trained personnel has been concentrated in a small area in Europe, the principal production being in Switzerland.

The present conflict has cut off the source of supply of instrument bearings and has left this country with inadequate facilities for their production. Accordingly, it has been necessary to find substitutes. Furthermore, because of the vital part that instruments play in devices for the armed forces and industry, it has been necessary to find a substitute which would not in any way impair the usefulness of the instruments even under abnormally severe conditions of use.

Fortunately, instrument manufacturers have a good deal of experience to fall back on. About 30 years ago, the present so-called "miniature instruments" (Figure 4) were introduced, and the demand for them has steadily increased, particularly in the communication industry. Because of the light weights of the moving systems and proportionately lower torques available, the radius of the pivot used was considerably smaller than that used in larger instruments. This created a demand for a sapphire jewel with a correspondingly smaller radius of the spherical surface in the bottom of the Vee.

In general, the problem of producing a sapphire jewel of the required shape resolves itself into that of cutting very accurately to shape a piece of sapphire, which is in a group of materials next in hardness to diamonds. The reason that the shape is particularly difficult is that the apex of the Vee must be accurately spherical, with a radius of from 0.002 to 0.004 inch, and the side tangent to the spherical surface must be straight. At the center of the spherical surface if, for example, the cut in the sapphire is made in a lathe, the linear cutting speed is zero and even at a speed of, say, 30,000 rpm at a distance of 0.001 inch from the center, the cutting speed is only 0.3 foot per sec-

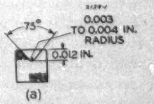

Figure 1a. Cross section of a sapphire jewel used for miniature instruments

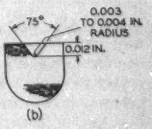

Figure 1b. Cross section of a hot-formed jewel as described in this paper

Paper 42-134, recommended by the AIEE committee on instruments and measurements for presentation at the AIEE summer convention, Chicago, Ill., June 22–26, 1942. Manuscript submitted April 20, 1942; made available for printing May 19, 1942.

F. K. McCUNE is assistant to the executive engineer, and J. H. Goss is engineer in the works laboratory, both with General Electric Company, West Lynn, Mass.

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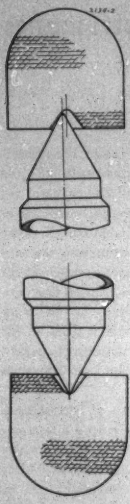

Figure 2. Scale drawing showing proportions and clearances of vertical shaft miniature instrument bearing

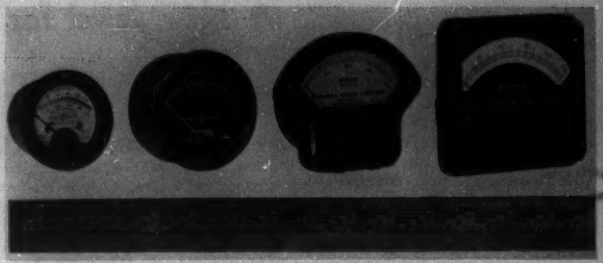

Figure 4 (above). A group of modern miniature instruments

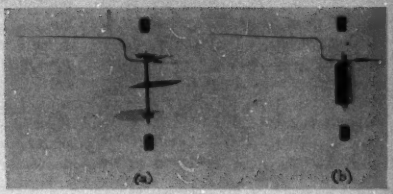

Figure 4a (right). Miniature instrument moving systems and jewel settings

(a). For a-c instruments
(b). For d-c instruments

ond. Also, as can be seen from the dimensions (Figure 1a), the cutting tool must be small in size. Therefore, the tendency in cutting, smoothing, or polishing is to produce a surface which is not truly spherical, but has either a lump in the center because of the low cutting speed, or a hollow which may be produced by crushing the center instead of cutting it.

As mentioned before, the small sapphire jewel for miniature instruments was necessary to limit the amount of side play in the jewel. As can be seen from Figures 2 and 3, the side play may amount to more than the end play. It is of importance both from the standpoint of its effect on mechanical clearances, and because excessive side play introduces uncertainty of pointer position. The latter is of most concern when the instrument may be used sometimes with shaft horizontal and at other times with shaft vertical. Referring to Figure 3, it is obvious that the only way to get a small degree of side play in a jewel of inherently large radius is to reduce the clearance between the pivots and the bottom of the jewels to a small fraction of a thousandth of an inch. This is an impractical solution, because of the hazard of very slight dimensional changes causing stickiness in the instrument, and because of the wedging action caused by the very small angle of slope of the jewel near the center.

The generally unsatisfactory contour in jewels available at the time led manufacturers to look for substitutes which could be produced by other methods. As a result of a large amount of development work done in the General Electric Company laboratories about 25 years ago, a method of producing a jewel by forming a drop of fused "hard glass" was developed. These jewels had very accurately controlled contours, since the glass could be made to almost any desired shape. The general shape is shown in Figure 1b. They also had very smooth highly polished surfaces. In respect to shape they were far superior to the sapphire then readily available. Such jewels had, however, two defects:

1. The manufacture had to be very carefully controlled and was not quite as simple as the description above may sound.
2. The jewel would show a microscopic indentation under an impact such as that produced by dropping the instrument, or by a heavy blow on the mounting panel.

This microscopic blemish in the surface would, however, in general not be noticeable in the performance of the instrument unless the pivot happened to run on the exact spot where the blemish had been made. Even in the latter case, the performance of the instrument would not be materially affected, unless a large number of pointer oscillations or the presence of vibration caused excessive wear at the roughened spot.

As has been mentioned before, a large number of these jewels were used, and their use probably served as an incentive to better the quality of sapphire jewels. In any event, after the hot-formed jewels had been used for several years, sapphire jewels became available with much improved contour, smaller radius of the spherical surface in the bottom of the Vee,

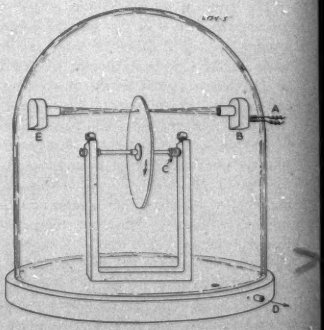

Figure 5. Apparatus for determining coefficient of friction

A—To amplifier and chronograph
B—Phototube
C—Vee jewel bearings or ring jewel bearings under test
D—To vacuum pump
E—Light source and lens

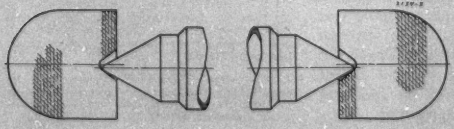

Figure 3. Scale drawing showing proportions and clearances of horizontal shaft miniature instrument bearing

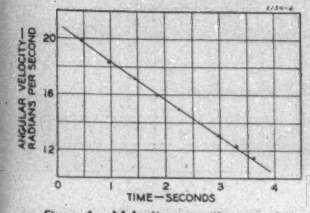

Figure 6. Velocity versus time curve

Deceleration 2.66 radians per second per second

and in every way suitable for instrument use. As a result, the use of the hot-formed jewel was practically abandoned although they have been used in certain instruments from time to time with satisfactory field performance.

The present emergency made necessary a review of the whole situation and the following steps were taken:

1. The performance of the hot-formed jewels and sapphire jewels was carefully re-evaluated.

2. A search for the optimum material for a hot-formed jewel was started, since it was recognized that new materials might be available which would be distinctly superior to that chosen as the best 10 or 15 years ago. The evaluation of relative performance of the hot-formed jewel and the sapphire jewel was carried out in the following manner with results as shown in the corresponding tables and figures:

(*a*). *Friction.* One criterion of instrument performance is that portion of the

Table I. Measured Coefficient of Friction When Run Against a High-Carbon Steel Pivot

Material	Form	Coefficient of Friction
Sapphire	Ring	0.140
Leaded Brass	Ring	0.188
Plastic *A*	Ring	0.160
Plastic *B*	Ring	0.190
Graphite	Ring	0.160
Sapphire	Vee	Range 0.15 to 0.19
Glass	Vee	0.18
Material *H* (Figure 11)	Vee	0.18
Ceramic polished	Vee	0.28
Ceramic unpolished	Vee	0.33

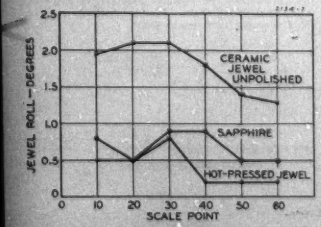

Figure 7. A comparison of jewel roll in a single instrument taken from three different sets of Vee jewels

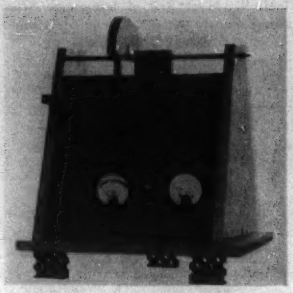

Figure 8a. Impact testing device—front view

Figure 8b. Impact testing device—back view

error in an instrument with a horizontal shaft caused solely by the friction between the pivot and jewel. This, when measured by noting the difference between upscale and downscale readings untapped in an instrument free from magnetic hysteresis, is known as jewel roll. Jewel roll, expressed in radians, is a function of moving system weight, restoring torque, radius of the pivot, and coefficient of friction between pivot and jewel. The formula has been given as follows: for the usual case where the end of the pivot is spherical and the surface of the jewel conical:[1]

$$\text{Jewel roll} \propto \frac{WCr}{K}$$

W—weight of the moving system in grams
C—coefficient of friction between the pivot and jewel
r—radius of the spherical end of the pivot in millimeters
K—restoring force in gram-millimeters per radian

In order to determine the friction between an instrument pivot and the corresponding jewel surface, two jewels of the material to be tested and a rotating member made up to approximately duplicate an instrument moving system were mounted in a vacuum (Figure 5). The moving system was made to rotate, the force causing this rotation was removed, and the deceleration measured. Figure 6 is a typical deceleration curve. From this deceleration, the moment of inertia, and dimensions of the parts involved, the coefficient of friction was calculated. While not having direct bearing on this investigation, certain data taken on ringstone jewels are included.

(*b*). Actual measurements of jewel roll with three materials involved were made using a very low torque instrument, with the results shown in Figure 7. These measurements were, of course, not nearly as accurate as the measurements under (*a*), but were simply confirmation that the measurements as taken in (*a*) are directly applicable to the problem.

(*c*). An impact device was prepared, two views of which are shown in Figure 8. After some experimentation, a test schedule was worked out as follows: The pendulum was raised ten degrees from the vertical, allowed to fall and strike the panel, and caught on the rebound. The instrument jewel roll was measured and the process repeated, the angle of drop being increased each time by ten degrees until 180 degrees was reached. Figure 9 shows the performance of two instruments mounted as shown on the same panel, one with sapphire jewels and one with hot-formed jewels from material *G* (Figure 11), which was the material used for jewels in the past.

(*d*). After impact a group of instruments, half with sapphire and half with hot-formed jewels of material *G*, were run from zero to full scale and back approximately 900,000 times, and the jewel roll again noted with results as shown in Table II.

All of the above were done with several different instrument designs and torques, and representative values are given in the tables. Conclusions from the above were that it was highly desirable to increase the impact strength of the hot-formed jewel.

(*e*). An arrangement as shown in Figure 10 was made by which a jewel could be accurately located below the opening of a glass tube. A hardened steel instrument pivot was placed in the Vee and struck by dropping a pellet weighing 0.1 gram upon it. As shown in the figure, the pellet was raised by a magnet to an exact height and released by removing the magnet. After each drop, the jewel was carefully examined under the microscope for any traces of fracture of the surface and another trial made if no fracture occurred. The method finally worked out as giving the most consistent results was to

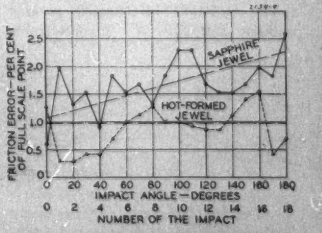

Figure 9. Increase of instrument friction as a result of successive impacts in ten-degree steps on panel impact device

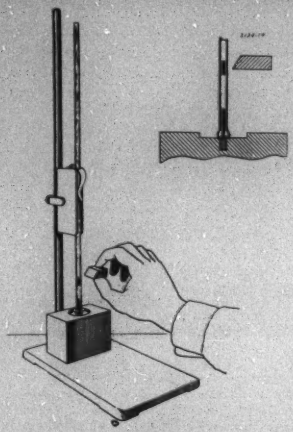

Figure 10. Jewel impacting device

drop the weight five times from a distance of 2 inches, five times from a distance of 6 inches, and five times from a distance of 12 inches. A jewel would be given a score of one for each time it successfully withstood a 2-inch drop, a score of three for each time it successfully withstood a 6-inch drop, and a score of six for each time it withstood a 12-inch drop. The total score of a group of five jewels was used in making the evaluation in each case. It should be noted that the pivots were initially selected by 100-diameter contour measurement and a 40-diameter visual inspection to be sure that they did not introduce another variable.

Figure 11 shows the comparative values of a number of different materials including material *G* which had been in use for many years.

It should be noted that the impact strength is not a function of material only, since jewels were actually produced from material *H* which varied in impact strength from practically zero when overstrained to a value of 30 when completely annealed as shown at *I*. The value plotted at *H* is the average which can be held for the optimum manufacturing process worked out.

The materials investigated covered ordinary soft glass *A*; a considerable

Table II. Jewel Roll of Instruments After Approximately 900,000 Pointer Movements Up and Down Scale

	Instrument No.	Angle* (in Degrees)
Hot-formed jewels	1	3.2
	2	3.2
	3	0.3
	4	1.5
	5	0.6
Sapphire jewels	1	1.0
	2	0.9
	3	1.0
	4	1.0
	5	1.2

Initial jewel roll was negligible.

* Instrument scale angle 90 degrees.

range of so-called "hard glasses," *B*, *C*, *D*, *E*, *F*, *G*, the material used some years ago, and *H*. Material *H* has a very high softening point and is unique in having a large percentage of alumina.

Since vibration is present in many instrument applications, *H* jewels were compared to sapphire in respect to bearing life under vibration. A table which gave each point in the instrument a circular motion in a plane 45 degrees from the horizontal with a diameter of 0.020 inch and a frequency of 1600 rpm was used. Results showed the two bearings to be comparable.

From an analysis of the above data and examination of the pivots and jewels it was obvious that material *H* represents very distinct progress over the previously used glass jewel. Since sapphire is harder than the steel pivot, the effect of heavy impact is to cause a deformation of the pivot. When this deformation occurs, the precision of the instrument is impaired, because the moving system is no longer supported by a smooth bearing, but is rolling on an irregularly shaped mushroomed pivot. This effect will always be present and will be noticeable at any part of the scale, since the whole end of the pivot is deformed. In the case of material *H*, the point at which the jewel material deforms is approximately the same as that at which the pivot deforms, so that up to this critical point, impact has no effect. Beyond this point, there is very

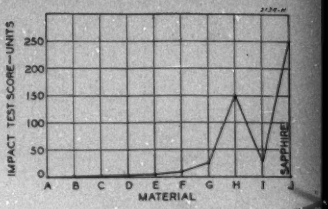

Figure 11. Impact tests on hot-formed jewels and on sapphire jewels

slight deformation of the pivots, and a minute area of the jewel surface is crushed. Because of the fact that the pivot flies up from its regular seat under impact, this deformed part of the jewel is very likely not to be at the point where the pivot usually travels and, therefore, is unlikely to affect the performance of the instrument in any way.

The technique of manufacturing instrument jewels with carefully controlled dimensions to give the impact strength of *H* has been worked out, and these can now be produced in quantities sufficient to assure that the jewel bearings will not be a limiting feature in the quantity of instruments which may be produced.

In conclusion, the original result desired was a jewel which could be produced in quantity, and which would involve the least possible sacrifice over sapphire for miniature instruments. The data indicate that there is little to choose between the new jewel and sapphire for actual miniature instrument application.

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A New Single-Phase-to-Ground Fault-Detecting Relay

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Synopsis: In the application of differential relays the need for a supervising relay which will detect the existence of a single-phase-to-ground fault condition to the exclusion of all others has frequently arisen. Heretofore, the only scheme available has been to utilize a relay energized by zero-sequence quantities. Generally, the relay has been energized by a current transformer connected in the station ground. Such a relay, however, will also detect the existence of a two-phase-to-ground fault and only partially solves the problem. The new relay described in this paper derives its operating force from the zero-sequence voltage at the bus and is restrained by the negative-sequence voltage at the bus. The addition of properly proportioned negative-sequence restraint provides the relay with a means of recognizing a single-phase-to-ground fault only. It is applicable on those systems where the zero-sequence impedance of the system exceeds the negative-sequence impedance by a reasonable margin.

Application

IN the application of differential relays to the protection of generating station busses, it is frequently the case that single-phase-to-ground fault protection only is desired. In such cases, the differential relay is connected in the residual circuit, or zero-sequence network, from the current transformers. Again, it is sometimes desirable to supplement three-phase differential relays with a fourth differential relay connected as above in order to obtain increased sensitivity for phase-to-ground faults. This latter condition is frequently encountered when systems are grounded through an impedance, so that the maximum value of phase-to-ground fault current is distinctly limited. In such cases the setting of the fourth or ground relay is considerably more sensitive than that of the phase relays, and the problem then becomes one of keeping the residual differential relay from tripping erroneously for heavy external phase-to-phase short circuits. Where conventional relays are used with current transformers, the major difficulty arises when a false differential current appears in the ground relay caused by unequal saturation of the various current transformers in the faulted phases, this condition being particularly emphasized by the presence of d-c transient. When the linear coupler relay scheme[1] is used, the fourth or ground relay set sensitive may also operate falsely for heavy external phase faults, not because of saturation, but depending upon the relative values of the maximum fault currents, the sensitivity of the relay, and the accuracy of the linear coupler transformers.

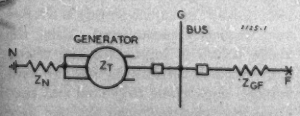

Figure 1. Schematic diagram of generator bus with fault on feeder circuit

Z_N—Grounding impedance
Z_T—Impedance of generator
Z_{GF}—Impedance from bus, G, to fault F
1, 2, 0—Where necessary, these subscripts are used in addition to those shown above to indicate the sequence network involved

A solution to this problem is to block out the ground relay for every type of fault except single-phase-to-ground. This applies whether conventional relays and current transformers, or the new linear-coupler scheme is used. The method is to connect the contacts of the supervising, or single-phase-to-ground fault-detecting relay, in series with the contacts of the main differential relay. If the latter relay then closes its contacts in error upon the occurrence of a heavy external two-phase-to-ground fault, for example, but the supervising relay properly maintains its contacts in the open position, no harm results. Up to now, no such supervising relay has been available which would recognize the existence of a single-phase-to-ground fault to the exclusion of all other types of faults. The new relay described in this paper is such a relay.

Paper 42-125, recommended by the AIEE committee on protective devices for presentation at the AIEE summer convention, Chicago, Ill., June 22-26, 1942. Manuscript submitted May 6, 1942; made available for printing May 29, 1942.

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Operating Principle

The new relay operates in accordance with the magnitude of the negative-sequence voltage and the zero-sequence voltage at the bus. The contact-closing

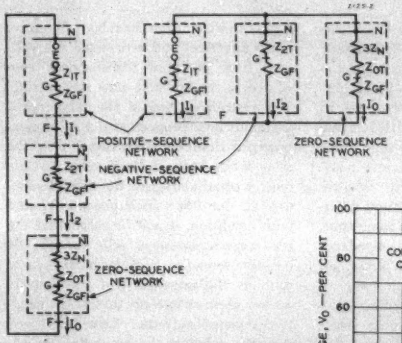


Figure 2. Sequence network connections for
(a). Single-phase-to-ground fault
(b). Two-phase-to-ground fault

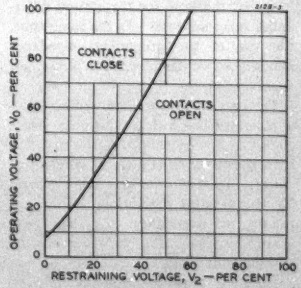


Figure 3. Typical operating characteristics of relay

The voltages shown are measured on the input side of the sequence filters
V_0—Zero-sequence voltage
V_2—Negative-sequence voltage

force in the relay is developed in proportion to the zero-sequence voltage, while the restraining force opposing contact closing is proportional to the negative-sequence voltage.

The proper application of the relay requires that the zero-sequence impedance of the system must exceed the negative-sequence impedance of the system by a reasonable margin. This requirement goes hand in hand with the need for the

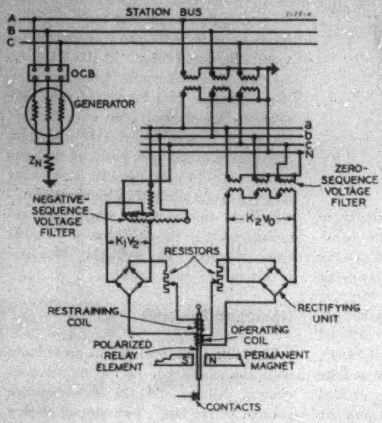


Figure 4 (left). Schematic diagram of connections of relay elements to station bus

K_1 and K_2 are design constants of the filter units

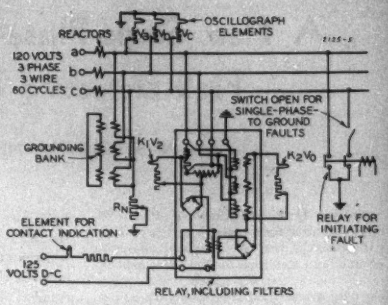


Figure 5 (right). Diagram of test connections

relay. On solidly grounded systems, where the ratio of zero-sequence to negative-sequence impedance at the generating station bus is low, ground-fault protection will generally be obtained by means of the phase differential relays, thus eliminating the need for the supervision of a nonexistent sensitive ground relay. When a grounding impedance is used, however, the need for the ground differential relay appears. At the same time, the use of the grounding impedance makes possible the application of the new supervising relay.

Figure 1 shows a schematic diagram of a generator bus with a fault on a feeder circuit. The generating capacity has been shown as an equivalent single generator. To make the case more general for the detailed derivations in the appendix, an impedance, Z_{GF}, has been assumed between the generator bus, G, and the fault at F.

Figure 2 shows the sequence network connections for single-phase-to-ground and two-phase-to-ground faults.[2] Phase-to-phase and three-phase faults need not be considered, inasmuch as no zero-sequence voltage is involved for these faults, and hence the relay would not experience any operating force. For convenience in simplifying the explanation of the relay operation, consider for the moment that the impedance, Z_{GF}, between the generator bus and the fault, F, is zero. This is equivalent to assuming that the fault occurs directly on the bus. Referring to Figure 2b for the two-phase-to-ground fault condition, it will be seen that the negative-sequence voltage to neutral at the bus is of necessity equal to the zero-sequence voltage to neutral, since the two networks are connected in parallel. Under this condition the relay will receive equal negative- and zero-sequences voltages from potential transformers connected to the bus and must not operate. The restraining coil of the relay must, therefore, be so proportioned as to be more powerful than the operating coil of the relay when both of these relay circuits receive equal voltages. Referring to Figure 2a for the single-phase-to-ground fault condition, it will be noted that the zero-sequence voltage will exceed the negative-sequence voltage in the same ratio as the impedance of the zero-sequence network exceeds that of the negative-sequence network. It will be noted that the value of the grounding impedance, Z_N, has been inserted in the zero-sequence network at three times its actual value in accordance with the conventional theorem. Since the same numerical value of current flows through the negative-sequence and zero-sequence network of Figure 2a, it follows that it is only necessary for the impedance of the zero-sequence network to be sufficiently high with respect to the impedance of the negative-sequence network to cause relay operation. The ohmic value of the grounding impedance, Z_N, will generally run quite high compared to the negative-sequence impedance of the generator, so that this condition is not difficult to meet.

Assume that the negative- and zero-sequence networks of Figure 2 are equal in ohmic value. It then follows that the negative- and zero-sequence voltages would be equal for each of these two cases. This is the limiting value in that if the relay-restraining and operating coils were so proportioned that the relay would be on the verge of closing, its contacts for a two-phase-to-ground fault, Figure 2b, then it would also be on the verge of closing its contacts for a single-phase-to-ground fault, Figure 2a. It follows more or less obviously that if Z_0 is greater than Z_2, the relay can be properly proportioned to discriminate between single-phase-to-ground and two-phase-to-ground short circuits. (Discrimination is automatic for phase-to-phase and three-phase short circuits, since no zero-sequence voltage is involved in these faults.)

It is desirable to establish a criterion for limits of application, and in this case it is felt that if the ratio Z_0/Z_2 is equal to or greater than 2/1, then a relay having characteristics similar to those illustrated in Figure 3, will meet the requirements satisfactorily.

Typical Application

Assume that Figure 1 represents a 13.2-kv installation and that the equivalent single generator has a rating of 20,000 kva. This is a relatively small capacity but is so chosen as to be on the pessimistic side in that the negative-sequence impedance will be relatively high. Typical values for the subtransient and negative-sequence reactance have been taken at 12 per cent each, and a zero-sequence reactance of four per cent has been assumed for the machine. The grounding impedance, Z_N, is assumed to be a two-ohm resistor, inasmuch as this is a value very frequently encountered. Using the above values of impedance and taking 7,620 volts to neutral as 100 per cent voltage, single-phase-to-ground and two-phase-to-ground faults on the bus were calculated. For the single-phase-to-ground fault, the negative-sequence voltage is 16.2 per cent and the zero-sequence voltage is 93.2 per cent. From the curve, Figure 3, when $V_2 = 16.2$ per cent, the required value of zero-sequence voltage, V_0, to operate the relay is 26 per cent. It is thus seen that the margin of the zero-

sequence voltage available over and above that required to barely operate the relay is ample. For the two-phase-to-ground fault, values of $V_1 = 49.5$ per cent and $V_0 = 49.5$ per cent were calculated for the assumed system. From the curve, it is found that at 49.5 per cent restraint voltage, the operating voltage, V_0, would have to be 79.5 per cent. Thus, the relay will not operate for the two-phase-to-ground fault. The calculations have been based on using the subtransient reactance of the machine in the positive-sequence network, since the relay is a high-speed relay.

While the relay has actually been made in the high-speed form, operating in one cycle or less, the principles involved are easily applied to other types of design so that the relay could be made "slow speed" if desired.

Figure 4 shows a schematic diagram of connections illustrating how the relay is energized from potential transformers connected to the station bus.

Tests

In order to check the actual operation of the relay against the theory, a test setup was made as shown in Figure 5. A system was represented in miniature. A variable resistor, R_N, was utilized as a grounding impedance in order that a minimum value for proper relay operation might be obtained and this checked against the calculations.

The location of oscillograph elements is shown in Figure 5. Elements were used to obtain traces of the phase-to-neutral voltages, V_a, V_b, and V_c, and the negative- and zero-sequence voltages, K_1V_1 and K_2V_0. The sixth element was used to obtain an indication of the operation of the relay contact. It should be noted that the output of the sequence filters is not numerically equal to the input quantities; hence the constants of proportionality, K_1 and K_2, have been used as indicated above.

Figure 6a shows the results of a test where phase *a* was faulted to ground. The ratio Z_0/Z_1 was 14.8 for this test. It will be observed that the relay properly closed its contact in 0.83 cycle. It will also be noted that there is a slight 60-cycle component and an appreciable harmonic component in the output of the negative-sequence filter prior to the fault. The 60-cycle component is explained by the fact that the filter was not perfectly balanced in its adjustment, and neither were the three-phase-to-neutral voltages perfectly balanced in the miniature setup. The existence of the harmonic component is occasioned by the fact that an iron core reactor is utilized in the filter design. In practice, the fact that the negative-sequence filter will have a combined output of fundamental and harmonic frequencies on the order of two volts or less under normal balanced conditions does not do any harm.

Figure 6b shows the results of a two-

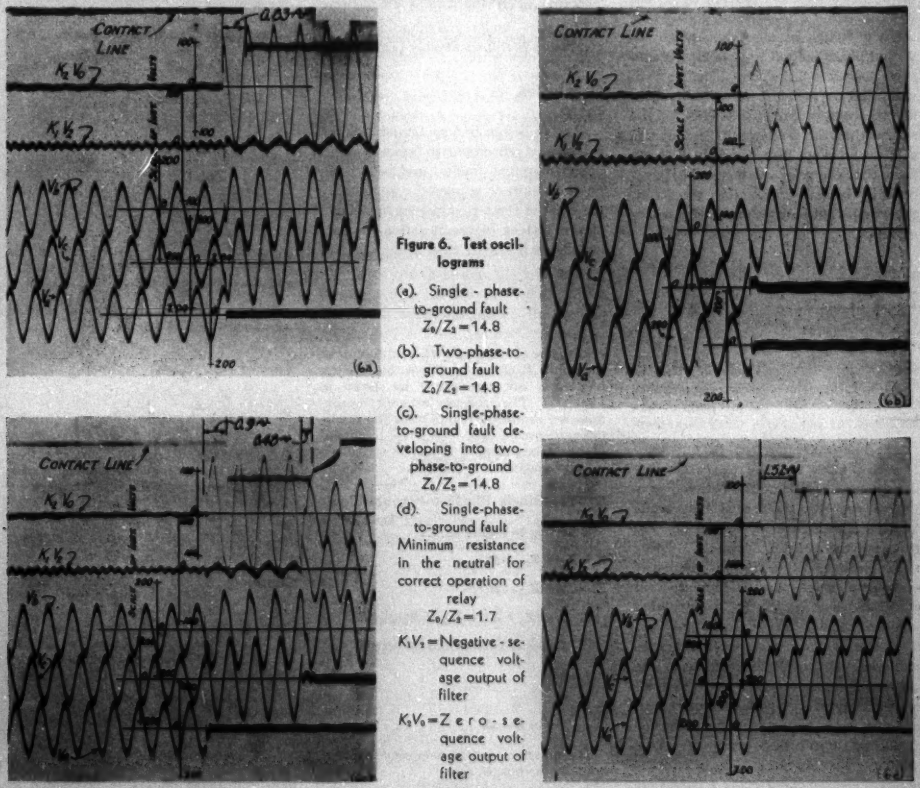


Figure 6. Test oscillograms

(a). Single-phase-to-ground fault $Z_0/Z_1 = 14.8$

(b). Two-phase-to-ground fault $Z_0/Z_1 = 14.8$

(c). Single-phase-to-ground fault developing into two-phase-to-ground $Z_0/Z_1 = 14.8$

(d). Single-phase-to-ground fault Minimum resistance in the neutral for correct operation of relay $Z_0/Z_1 = 1.7$

K_1V_1 = Negative-sequence voltage output of filter

K_2V_0 = Zero-sequence voltage output of filter

phase-to-ground fault on phases a and c. The ratio $Z_0/Z_1=14.8$ was kept the same as before. The calibration of the oscillograph elements remained the same, as in all cases to follow. The contacts of the relay did not operate. The relative magnitude of the deflections of the elements measuring K_1V_2 and K_2V_0 should be compared for Figures 6a and 6b.

In Figure 6c, the results are shown for a fault which started as one phase-to-ground and developed into a two-phase-to-ground fault. As before, the ratio of Z_0/Z_1 was kept at 14.8. The contacts first closed, as they should, in 0.9 cycle. When the second phase faulted to ground, the contacts opened in 0.48 cycle. The film indicates that the contacts were slow in opening the contact circuit. This is for the reason that the d-c current used in this element was kept high—just about at the limit that the relay contacts would successfully break. In practice, these contacts would not be expected to open heavy currents.

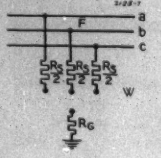


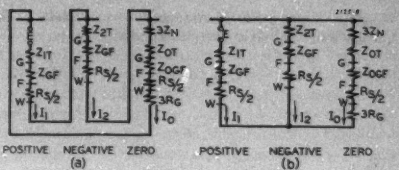
Figure 7. Diagram showing arc resistance at the point of fault

The resistance, R_N, was next reduced to such a value that the relay would just discriminate satisfactorily between one-phase- and two-phase-to-ground faults and the film, Figure 6d, was taken. For this case, the ratio Z_0/Z_1 was 1.7. Using the impedance values for the miniature system, a single-phase-to-ground fault condition was calculated. The calculated values were: $V_0=58.4$ per cent and $V_2=34.2$ per cent. At a negative-sequence restraining voltage of 34.2 per cent, the curve, Figure 3, indicates that the zero-sequence operating voltage required to just overcome this restraint should be not more than 54 per cent. An apparent error of 8.2 per cent is indicated in the calculations. This is explained on the basis that there were errors in the miniature setup which could be eliminated if it were found necessary to run the test with precision laboratory accuracy. The errors include the slight unbalance in the negative-sequence filter which was previously mentioned, a slight mutual coupling which existed between the reactors used in the supply circuit, and the fact that the burden of the sequence filters was appreciable with respect to other constants of the miniature system. None of these factors was taken into consideration in the calculations.

Figure 8. Connections of sequence networks for

(a). Single-phase-to-ground fault

(b). Two-phase-to-ground fault



In Figure 6d, the contact closing time 1.52 cycles under minimum operating conditions is still reasonably fast.

Conclusion

A relay design is now available which will properly discriminate between single-phase-to-ground faults and all other types of faults on grounded systems when the ratio of the zero-sequence impedance of the system to the negative-sequence impedance is greater than unity.

Appendix

Let it be assumed that the fault occurs at the point, F, of Figure 1, and that the arc resistances are represented as shown in Figure 7. The sequence network connections are shown by Figure 8 for the single-phase-to-ground and two-phase-to-ground faults. The points G, F, and W are shown in these diagrams.

Case I—Single-Phase-to-Ground Fault

Referring to Figure 8a, let

$$Z_1=Z_{1T}+Z_{GF}+R_{s/2} \tag{1}$$

$$Z_2=Z_{2T}+Z_{GF}+R_{s/2} \tag{2}$$

and $$Z_0=3Z_N+Z_{0T}+Z_{0GF}+R_{s/2}+3R_G \tag{3}$$

In the series connections of networks

$$I_1=I_2=I_0 \tag{4}$$

and $$I_1=\frac{E}{Z_1+Z_2+Z_0} \tag{5}$$

The negative- and zero-sequence voltage drops at the bus, G, are

$$E_{2G}=0-I_2Z_{2T} \tag{6}$$

and $$E_{0G}=0-I_0(3Z_N+Z_{0T}) \tag{7}$$

Substituting I_2 for I_0 (since these are equal, equation 4) in equation 7, and dividing equation 6 by equation 7, a ratio, R_1, is obtained

$$R_1=\frac{E_{2G}}{E_{0G}}=\frac{Z_{1T}}{(3Z_N+Z_{0T})} \tag{8}$$

Equation 8 gives the relationship existing between the negative-sequence restraining voltage and the zero-sequence operating voltage when the relay must operate.

Case II—Two-Phase-to-Ground Fault

Referring to Figure 8b, let equations 1, 2, and 3 stand as before. In this case, however

$$I_1=\frac{E(Z_2+Z_0)}{Z_1Z_2+Z_1Z_0+Z_2Z_0} \tag{9}$$

$$I_2=-I_1\frac{Z_0}{Z_2+Z_0} \tag{10}$$

$$I_0=-I_1\frac{Z_2}{Z_2+Z_0} \tag{11}$$

As in Case I,

$$E_{2G}=0-I_2Z_{2T} \tag{6}$$

and $$E_{0G}=0-I_0(3Z_N+Z_{0T}) \tag{7}$$

Substituting for I_2 and I_0 in terms of I_1, equations 6 and 7 become

$$E_{2G}=0+I_1\frac{Z_0}{Z_2+Z_0}Z_{2T} \tag{12}$$

$$E_{0G}=0+I_1\frac{Z_2}{Z_2+Z_0}(3Z_N+Z_{0T}) \tag{13}$$

A new ratio, R_2, between the negative-sequence restraining voltage and zero-sequence operating voltage, is obtained by dividing equation 12 by equation 13

$$R_2=\frac{Z_0Z_{2T}}{Z_2(3Z_N+Z_{0T})} \tag{14}$$

Summary

If the relay is to discriminate properly between the conditions of case I and case II, then the ratio, R_2, must be greater than the ratio, R_1. Dividing equation 14 by equation 8, there results

$$R_2/R_1=\frac{Z_0}{Z_2} \tag{15}$$

Equation 15 indicates that if $Z_0/Z_2>1$, then $R_2/R_1>1$, and the relay will receive more restraining voltage in proportion to operating voltage for the two-phase-to-ground fault condition than it will for the single-phase-to-ground fault.

References

1. Linear Couplers for Bus Protection, E. L. Harder, E. H. Klemmer, W. K. Sonnemann, E. C. Wentz. AIEE Transactions, volume 61, 1942, May section, pages 241–8.

2. Symmetrical Components (book), Wagner, Evans. McGraw-Hill Book Company, New York, N. Y.

On Eddy Currents in a Rotating Disk

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NONMEMBER AIEE

A DEVICE which often occurs in electric machines and instruments consists of a relatively thin conducting disk rotating between the pole pieces of a permanent magnet or electromagnet. The author has received inquiries as to the method of calculating the paths of the eddy currents and the torque in such cases. The following rather simple method, which is quite accurate for a permanent magnet, seems not to be described in the literature. It assumes that the disk is so thin that the skin effect can be neglected. This is true for all frequencies that can be produced mechanically. To facilitate calculation in the special case of circular poles it is also assumed that $2\pi\omega ab\gamma = \epsilon a$ is much less than one where ω is the angular frequency of rotation in radians per second, a the pole-piece radius, b the disk thickness, and γ the electric conductivity, all in centimeter-gram-second electromagnetic units. This produces a fractional error of less than ϵa in the eddy current densities and of less than $(\epsilon a)^2$ in the torque. In the case of the electromagnet the situation is complicated by the presence of the permeable pole pieces in the magnetic field of the eddy currents. This may send a large demagnetizing flux through the electromagnet. An approximate solution for this case will be considered.

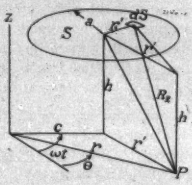

Figure 1. Geometrical relations for derivation of formulas for stream function

Maxwell's Formula

This calculation starts from a formula given by Maxwell in 1873,[1] but apparently little known to engineers. To apply it one should know its derivation which, as given by Maxwell, is difficult for modern students to follow. A simplified proof which brings out the points essential for our problem is given below.

The object is to calculate the magnetic induction $\boldsymbol{B}$ produced by the eddy currents of density $\boldsymbol{i}$ induced in a thin plane sheet of thickness b, unit permeability and conductivity γ lying in the xy plane by a fluctuating magnetic field of induction $\boldsymbol{B}'$. Evidently the only components of $\boldsymbol{i}$ effective in producing magnetic effects parallel its surface. Let the eddy currents be confined to a finite region of the sheet which may or may not extend to infinity, and let us define the stream function $U(x, y)$ at any point in the sheet to be the current flowing through any cross section of the sheet extending from P to its edge. The line integral of $\boldsymbol{B}$ or $\boldsymbol{H}$ over the closed path that bounds this section equals $4\pi U$. From symmetry the contribution from the upper and lower halves of the path is the same so we may write

$$4\pi U = \oint \boldsymbol{B}\cdot d\boldsymbol{s} = \mp 2\int_y^\infty B_x dx = \pm 2\int_y^\infty B_y dy \qquad (1)$$

where the choice of sign depends on the side of the sheet chosen for the integration. Differentiating this equation gives

$$bi_x = -\frac{\partial U}{\partial y} = \pm\frac{B_y}{2\pi} \qquad bi_y = -\frac{\partial U}{\partial x} = \mp\frac{B_x}{2\pi} \qquad (2)$$

These equations connect the eddy current density with the tangential components of the magnetic induction $\boldsymbol{B}$ produced by $\boldsymbol{i}$ at the surface of the sheet.

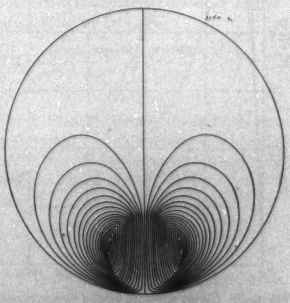

Figure 2. Lines of flow of eddy currents induced in rotating disk by single circular magnet pole

The eddy currents are generated not only by the changes in the magnetic induction $\boldsymbol{B}'$ of the external field, but also by the changes of the magnetic induction $\boldsymbol{B}$ of eddy currents elsewhere in the sheet. One of Maxwell's equations combined with Ohm's law gives the induced current to be

$$\nabla\times\boldsymbol{E} = \nabla x\frac{\boldsymbol{i}}{\gamma} = -\frac{\partial}{\partial t}(\boldsymbol{B}'+\boldsymbol{B}) \qquad (3)$$

Writing out the z component of this equation and using equation 2 give

$$\frac{1}{\gamma}\left(\frac{\partial i_y}{\partial x}-\frac{\partial i_x}{\partial y}\right) = \mp\frac{1}{2\pi b\gamma}\left(\frac{\partial B_x}{\partial x}+\frac{\partial B_y}{\partial y}\right) = -\frac{\partial}{\partial t}(B_z'+B_z) \qquad (4)$$

Another of Maxwell's equations states that

$$\nabla\cdot\boldsymbol{B} = \frac{\partial B_x}{\partial x}+\frac{\partial B_y}{\partial y}+\frac{\partial B_z}{\partial z} = 0 \qquad (5)$$

Combining equations 4 and 5 gives

$$\frac{\partial(B_z'+B_z)}{\partial t} = \frac{1}{2\pi b\gamma}\frac{\partial B_z}{\partial z} \qquad (6)$$

When $\partial B_z'/\partial t$ is known, this equation gives the boundary condition on $\boldsymbol{B}_z$ in the plane of the sheet. This, combined with the equations $\nabla\times\boldsymbol{B}=0$ and $\nabla\cdot\boldsymbol{B}=0$ which hold outside the sheet, and the fact that $\boldsymbol{B}$ vanishes at infinity serves to determine $\boldsymbol{B}$ everywhere. By equations 1 and 2 the current density and stream function anywhere in the sheet can be found.

The explicit expression for $\boldsymbol{B}$ in terms

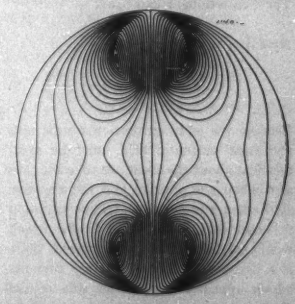

Figure 3. Lines of flow of eddy currents induced in rotating disk by two circular magnet poles

Figure 4. Geometrical relations for calculation of demagnetizing flux

Paper 42-140, recommended by the AIEE committee on basic sciences for presentation at the AIEE summer convention, Chicago, Ill., June 22–26, 1942. Manuscript submitted December 12, 1940; made available for printing May 20, 1942.

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of B' which was given by Maxwell[1] can be obtained as follows. The right side of equation 6 is finite at all times which means that if $\Delta t \to 0$ then $\Delta(B_z'+B_z) \to 0$. Thus an abrupt change in B' instantaneously induces eddy currents such as will maintain $B'+B$ unchanged in the sheet. Therefore, for a specified change in B' the initial value of B is known, and, if no further changes in B' occur its subsequent values as the eddy currents decay are found by putting $\partial B'/\partial t = 0$ in equation 4 and solving. A second abrupt change in B' produces a second set of eddy currents, and so forth. At any instant the actual field of the eddy currents is a superposition of these. As the magnitudes of the discontinuous changes in the external field become smaller, and the intervals between them shorter, we approach as a limit a continuously changing magnetic field.

Suppose that the sources of the inducing field lie above the xy plane where $z>0$. At $t=0$ the source changes abruptly the induction being $B_1' = F_1(x, y, z)$ when $-\infty < t < 0$ and $B_2' = F_2(x, y, z)$ when $0 < t < \infty$. As just shown the eddy currents generated at $t=0$ initially keep the field on the negative side of an infinite sheet unchanged. When $z<0$ we have therefore

$$B_{t=0} = B_1' - B_2' = F_1(x, y, z) - F_2(x, y, z) \quad (7)$$

Since B_z' is not a function of t, equation 6 reduces to

$$\frac{\partial B_z}{\partial t} = \frac{1}{2\pi b\gamma} \frac{\partial B_z}{\partial z} \quad (8)$$

These equations, 7 and 8, are satisfied by

$$B = F_1\left(x, y, z + \frac{t}{2\pi b\gamma}\right) - F_2\left(x, y, z + \frac{t}{2\pi b\gamma}\right) \quad (9)$$

Because the eddy currents must die out, and their magnetic field must be symmetrical about the sheet, we take the plus sign when z is positive and the negative sign when z is negative. Thus equation 9 shows that, in addition to B_z' which would exist if no sheet were present, there is a decaying field due to eddy currents which appears, from either side of the sheet, to be caused by a pair of images receding with uniform velocity $1/(2\pi b\gamma)$. Suppose our inducing field has the form

$$B' = F(t, x, y, z) \quad (10)$$

The change in this field in an infinitesimal time interval $d\tau$ is given by

$$\frac{\partial B'}{\partial t} d\tau = \frac{\partial}{\partial t} F(t, x, y, z) d\tau \quad (11)$$

The initial field of the eddy currents formed in that interval must be equal and opposite to this and must die out as if their source moved away with a uniform speed $1/(2\pi b\gamma)$. Thus the eddy currents at a time t due to a change in the interval $d\tau$ at a time τ before t is given by

$$dB = -\frac{\partial}{\partial t} F\left(t-\tau, x, y, z + \frac{\tau}{2\pi b\gamma}\right) d\tau \quad (12)$$

This is Maxwell's formula. It has many applications.[2] When the field is produced by moving permanent magnets, it is convenient to express U in terms of the scalar magnetic potential Ω. Since we have unit permeability we may write

$$U = \frac{1}{2\pi} \int_r^\infty B_r dr = \frac{-1}{2\pi} \int_r^\infty \frac{\partial \Omega}{\partial r} dr = \frac{\Omega}{2\pi} \quad (13)$$

Application to Magnet Moving in a Circle

We now take the case of a magnetic field produced by a long right circular cylinder of radius a, uniformly and permanently magnetized parallel to its axis, so as to give a total flux Φ. The magnetic pole density in the face is therefore $\Phi/(2\pi a)^2$. This magnet moves in a circle with a uniform angular velocity ω its axis being c centimeters from the z axis, and its lower end h centimeters above the $z=0$ plane in which lies an infinite plane sheet of thickness b and conductivity γ. Its upper end is too remote for consideration. Polar co-ordinates will be written unprimed or primed according as they refer to the axis of rotation or to the pole-piece axis. The scalar magnetic potential Ω' of its lower face, of area S, at the point P is seen from Figure 1 to be

$$\Omega' = \frac{\Phi}{(2\pi a)^2} \int_S \frac{dS}{R_1} = \frac{\Phi}{(2\pi a)^2} \times \int_0^a \int_0^{2\pi} \frac{r_1' dr_1' d\theta'}{\sqrt{h^2 + r_1'^2 + r'^2 - 2r_1' r' \cos\theta'}}$$

where $r'^2 = r^2 + c^2 - 2rc \cos(\omega t + \theta)$. This combined with equations 12 and 13 give the stream function to be

$$U = \frac{\Phi}{(2\pi)^2 a^2} \int_0^a \int_0^{2\pi} \int_0^\infty \frac{\partial}{\partial t} \times \left(\frac{r_1' dr_1' d\theta' d\tau}{\sqrt{h_\tau^2 + r_1'^2 + R_\tau'^2 - 2r_1' R_\tau' \cos\theta'}} \right) \quad (14)$$

where $R_\tau'^2 = r^2 + c^2 - 2rc \cos(\omega(t-\tau)+\theta)$ and $h_\tau = h + \tau/(2\pi b\gamma) = h + u$. Let us now bring the pole piece down close to the plate so that $h_\tau = \tau/(2\pi b\gamma)$, and bring up a similar pole of opposite sign from the other side, so that the eddy current density is doubled. We now carry out the differentiation with respect to t and set $t=0$ so that the $\theta=0$ line bisects the pole piece when $t=0$. The integral then becomes

$$U = \frac{rc\Phi\epsilon}{\pi(2\pi a)^2} \int_0^a \int_0^{2\pi} \int_0^\infty \frac{\sin(\theta+\epsilon u)(R_u' - r_1'\cos\theta') r_1' dr_1' d\theta' du}{R_u'(u^2 + r_1'^2 + R_u'^2 - 2R_u' r_1' \cos\theta')^{3/2}} \quad (15)$$

where $\epsilon = 2\pi\omega b\gamma$ and $R_u'^2 = r^2 + c^2 - 2rc \times \cos(\theta + \epsilon u)$. For 3,000 rpm with a copper sheet 0.25 millimeter thick $\epsilon \approx 0.01$ so that u^2 in the denominator has reached the value 100 when ϵu reaches 0.1. In calculating such a quantity as the torque where the current density is integrated over the pole piece, the neglect of ϵ produces a fractional error less than $(\epsilon/a)^2$, so that the result should be good to one per cent for a sheet one millimeter thick. We may therefore drop the ϵ terms so that R_u' becomes the r' in Figure 1 and integrate with respect to u giving

$$U = \frac{K \sin\theta}{r'} \times \int_0^a \int_0^{2\pi} \frac{(r' - r_1'\cos\theta') r_1' dr_1' d\theta'}{r'^2 + r_1'^2 - 2r' r_1' \cos\theta'} \quad (16)$$

where we have written K for the coefficient of the integral in equation 15. The integral with respect to θ', from Dwight's table of integrals 860.2, is zero when $r' < r_1'$ and π/r' when $r' > r_1'$. Thus the upper limit for the r_1' integration is a when $r' > a$ and r' when $r' < a$, which gives

$$r' > a \qquad U = \frac{\omega r c b \gamma \Phi \sin\theta}{2 r'^2} \quad (17)$$

$$r' < a \qquad U = \frac{\omega r c b \gamma \Phi \sin\theta}{2\pi a^2} \quad (18)$$

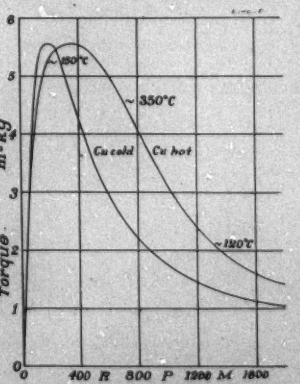

Figure 5. Curves showing torque versus speed for large disk rotating between the four rectangular pole pairs of an electromagnet, measured by Lentz

The next question is how to restrict the eddy currents to the interior of the disk bounded by the circle $r=A$. We observe that if we use equation 15 to calculate U for a second magnet also carrying a flux Φ but with circular pole pieces of radius $a''=Aa/c$ centered at $c''=A^2/c$, so that $R_u''^2=r^2+(A^2/c)^2-2r(A^2/c)\cos(\theta+\epsilon u)$, and change the variables of integration from r_1' to $r_1'A/c$, and from u to Au/c, then the resultant expression is identical with equation 15, except that we have cR_u''/A instead of R_u' and $A\epsilon/c$ instead of ϵ. But when $r=A$ we see that $cR_u''/A=R_u'$, so that both magnets, one outside and one inside the circle $r=A$, give the same U on this circle. Furthermore by taking the air gap in each magnet small, the fluxes are confined to the areas under the pole pieces, so that neither induces directly eddy currents on the other side of the circle $r=A$. It is evident that if the fluxes from the two magnets cut the sheet in opposite directions, then $U=0$ when $r=A$ and the currents induced by the inner pole are kept inside the circle. This is exactly the boundary condition for a disk of radius A, except that the calculated system includes the currents induced in the region $r<A$ by the magnetic field of the eddy currents in the region $r>A$, which does not exist in the case of the disk. This field is proportional to $\Phi\epsilon$ which is, by hypothesis, small compared with Φ, and in addition the source is further away, so that the fractional error in U will be less than ϵ. We should note also from the symmetry that the radial component of these secondary currents is opposite in sign on the two sides of the $\theta=0$ line, so that their effect cancels out completely in calculating the torque which therefore should be accurate to terms in ϵ^2. The contribution to U from the outer magnet is found by putting $c^2R''^2/A^2$ for R^2 in equation 17. Adding this to equations 17 and 18, we obtain for the stream function of the eddy currents in the disk

$$R>a \quad U=\frac{\omega rcb\gamma\Phi\sin\theta}{2\pi}\left(\frac{1}{r^2+c^2-2rc\cos\theta}-\frac{A^2}{c^2r^2+A^4-2rcA^2\cos\theta}\right) \tag{19}$$

$$R<a \quad U=\frac{\omega rcb\gamma\Phi\sin\theta}{2\pi a^2}\left(1-\frac{A^2a^2}{c^2r^2+A^4-2rcA^2\cos\theta}\right) \tag{20}$$

The torque may be calculated by integrating the product of the radial component of the current by the magnetic induction and by the lever arm and integrating over the area S of the pole piece. Thus, using equation 2, we have

$$T=\int_S rbi_r\Phi\,dS=\frac{\Phi}{\pi a^2}\int_{c-a}^{c+a}\int_{-\theta_1}^{+\theta_1}r\frac{\partial U}{\partial r}r\,dr\,d\theta$$

where θ_1 and r are connected by the relation $r^2+c^2-2rc\cos\theta_1=a^2$. Substituting for U from equation 20 and integrating with respect to θ give

$$T=\frac{\omega cb\gamma\Phi^2}{\pi^2a^4}\times\int_{c-a}^{c+a}\left(r^2\sin\theta_1-\frac{a^2A^2r^2\sin\theta_1}{c^2r^2+A^4-2A^2rc\cos\theta_1}\right)dr \tag{21}$$

The integration is simplified by taking a new variable u so that $4acu^2=r^2-(c-a)^2$ which gives the limits 0 and 1. Thus we obtain, writing out ϵ,

$$T=\frac{\omega b\gamma\Phi^2c^2}{2\pi a^2}\left(1-\frac{A^2a^2}{(A^2-c^2)^2}\right)=\omega\gamma\Phi^2D_1 \tag{22}$$

This formula gives the torque in dyne centimeters when ω is in radians per second, Φ in maxwells, a, b, c, and A in centimeters and γ in electromagnetic units. If we are given the volume resistivity ρ of the disk in ohm-centimeters $\gamma=10^{-9}/\rho$.

If the magnet is fixed, and the disk rotates, the arrangement described exerts an undesired force on the disk axis which may be avoided by using two identical magnets on opposite sides of the axis and equidistant from it. This approximately doubles the torque given by equation 22. The additional torque from the eddy currents of one magnet flowing under the poles of the other may be found by an integral similar to equation 21 which is

$$T'=\frac{\omega b\gamma\Phi^2c}{\pi^2a^2}\int_{c-a}^{c+a}\left(\frac{r^2\sin\theta_1}{r^2+c^2+2rc\cos\theta_1}-\frac{r^2A^2\sin\theta_1}{r^2c^2+A^4+A^2rc\cos\theta_1}\right)dr \tag{23}$$

Integrating by the same substitutions as equation 21, adding to equation 22 and multiplying by two give

$$T=\frac{\omega b\gamma\Phi^2c^2}{\pi a^2}\left(\frac{4c^2+a^2}{4c^2}-\frac{2a^2A^2(A^4+c^4)}{(A^4-c^4)^2}\right)=\omega\gamma\Phi^2D_2' \tag{24}$$

This holds when the two magnet fields are antiparallel. If we subtract the integral of equation 23 from equation 22 and multiply by two we get

$$T=\frac{\omega b\gamma\Phi^2c^2}{\pi a^2}\left(\frac{4c^2-a^2}{4c^2}-\frac{4a^2c^2A^4}{(A^4-c^4)^2}\right)=\omega\gamma\Phi^2D_2'' \tag{25}$$

This holds when the two magnetic fields are parallel. The arrangement of equation 24 gives more torque than that of equation 25. The eddy-current flow lines corresponding to constant values of U as calculated from equations 19 and 20 applied to the cases of equations 22 and 24 are shown in Figures 2 and 3 where $a=\sqrt{7}$ cm, $c=7$ cm, $A=10$ cm and $\omega b\gamma\Phi/(2\pi)=3.5$. The value U on the outer boundary is zero and changes by steps of one in Figure 2 and steps of two in Figure 3.

Demagnetizing Effects

So far the magnet pole pieces have been assumed to be so hard that they do not short-circuit the flux of the eddy currents. This is not true for the permeable pole pieces of an electromagnet, whose effect may be calculated approximately by observing that the current $2U$ is enclosed by the rectangular path 1-2-3-4-1 in Figure 4, which lies in the upper and lower pole pieces except where it cuts across the disk and gap normally at $r=r_1$ and $\theta=\pm\theta_1$. If the reluctance of this circuit lies entirely in the air gaps, each of length g, then the magnetic flux density B_e due to the eddy currents alone at r_1, $\pm\theta_1$ is $4\pi U/g$. Substituting for U from equation 20 and writing as before $\epsilon=2\pi\omega b$ gives

$$B_e=\frac{cer_1\Phi\sin\theta_1}{\pi a^2g}\left(1-\frac{A^2a^2}{c^2r_1^2+A^4-2r_1cA^2\cos\theta_1}\right) \tag{26}$$

This shows that when b and g are comparable in size B_e cannot be neglected compared with the original flux density $\Phi/(\pi a^2)$. The $\sin\theta_1$ term shows that the radial component of the eddy currents induced by B_e have opposite signs under the two halves of the pole piece, so that they contribute nothing directly to the torque, but on the other hand they form closed circuits about the central portion and so produce a demagnetizing magnetomotive force in the electromagnet. The

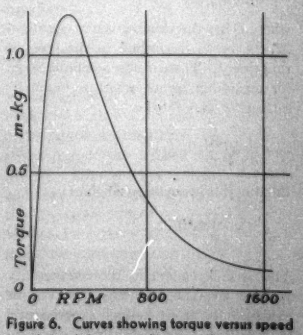

Figure 6. Curves showing torque versus speed for a large disk rotating between the single pair of circular pole pieces of an electromagnet as given by equations 22, 27, and 28

stream function U_e of these eddy currents is calculated as U is, but to simplify matters we carry out the operations from equations 14 to 16 for a single element of the pole face, along with its image element outside the circle $r=A$. We then give each element the strength indicated in equation 26 and set up a definite integral for U over the pole-piece area. This method is less exact than setting up equation 14 for the whole face, because it ignores that part of the flux threading dS from the current induced by B_e outside this area, which is of the order $\epsilon B_e dS$. The eddy currents U_e are evidently equivalent to a magnetic shell of variable strength U_e in the sheet and to get $\mathfrak{F}_e$ the demagnetizing magnetomotive force we must find the equivalent uniform shell. Thus we have

$$\mathfrak{F}_e=\frac{1}{\pi a^2}\int_S U_e\,dS$$

where S is the area of the pole face. We now have a complicated quadruple integral involving the variables r', R', θ' and θ_1' whose evaluation can be simplified somewhat by integrating in the proper order. The result is

$$\mathfrak{F}_e=\frac{\omega^2 b^2\gamma^2 c^2}{4g}\Phi\left(1-\frac{2a^2A^2(A^2+c^2)}{c^2(A^2-c^2)^2}+\frac{2A^4}{c^4}\log_e\frac{(A^2-c^2)^2}{(A^2-c^2)^2-c^2a^2}\right)=\beta^2\gamma^2\omega^2\Phi \quad (27)$$

If the flux penetrating the sheet at rest is Φ_0, then when in motion we have, if $\mathfrak{R}$ is the reluctance of the electromagnet, $\Phi=\Phi_0-\beta^2\gamma^2\omega^2\Phi/\mathfrak{R}$, so that

$$\Phi=\frac{\mathfrak{R}\Phi_0}{\mathfrak{R}+\beta^2\gamma^2\omega^2} \quad (28)$$

The expressions for the torque now become

$$T=\frac{\omega\gamma\mathfrak{R}^2\Phi_0^2 D}{(\mathfrak{R}+\beta^2\gamma^2\omega^2)^2} \quad (29)$$

where D has the values given in equations 22, 24, or 25, according to the pole arrangement. There is now a definite speed for maximum torque which is found by setting $\partial T/\partial\omega=0$ to be

$$\omega_m=\frac{1}{\beta\gamma}\sqrt{\frac{\mathfrak{R}}{3}} \quad (30)$$

Putting this in equation 29 gives

$$T_m=\frac{3\sqrt{3\mathfrak{R}}\Phi_0^2 D}{16\beta} \quad (31)$$

This is independent of the conductivity which is surprising, although there is some evidence for it in Lentz's experimental curves shown in Figure 5 which give hot and cold copper disks the same T_m for different ω_m.

These calculations of demagnetizing effects have been worked out for a single pole. For an even number of poles with alternating signs, we have seen that the torque per pole is increased, but the demagnetizing forces are also increased so that the torque obtained by multiplying equation 29 by the number of poles will probably not be far wrong. The speed for maximum torque given by equation 30 will certainly be decreased, perhaps considerably, because of the increase in β.

The only formula we can find for this torque is one derived by Rüdenberg.[3] This formula is written as a double infinite series and is derived by considering a thin conducting strip bounded by straight lines which moves lengthwise in the narrow gap between magnetic poles with rectangular faces. The fields of adjacent poles are antiparallel, so that the inducing fields can be expanded in a double series of odd harmonics. This formula was checked qualitatively by Zimmermann,[4] but could not be verified quantitatively, as the theoretical and experimental boundary conditions did not agree. Lentz found only those terms involving the lengthwise harmonics were of importance and dropped the rest. His experimental brake had the center of the disk removed to simulate a ring whose width roughly equaled that of the postulated strip. His four poles were so far apart that their action was nearly independent. We have redrawn in Figure 5, his experimental curves giving the torque in meter kilograms against angular velocity in revolutions per second. The ring had inner and outer radii of 5 centimeters and 25 centimeters and was 0.4 centimeter thick. The air space was 1.2 centimeters, and the centers of the rectangular pole pieces were 20.75 centimeters from the rotation axis and were 6 centimeters (radial) by 8 centimeters (tangential). The inducing field was 2,150 gauss at rest. The figures on the hot copper curve show the estimated stable mean temperature for that speed.

A direct quantitative comparison of our formula with Lentz's data is difficult, because he used rectangular poles, his air gap was so large as to spread the inducing field over an unknown area, the center of his disk was cut away, and we do not know where his flux density was measured. Although our formulas are inaccurate for such large dimensions at the high speeds, it is interesting to see what results they give for a comparable case. Let us take $b=0.4$ cm, $A=25$ cm, $a=4$ cm, $c=21$ cm, $g=0.6$ cm, $B=2{,}000$ gauss and assume the reluctance entirely in the air gap. In equation 22, $D_1=1.23$, in equation 27, $\beta=3.85$ and in equation 28 $\mathfrak{R}=0.012$. The angular velocity for maximum torque for copper ($\gamma=1/1{,}700$) is given by equation 30 to be 27.9 radians per second or 267 rpm. T_m is 1.15×10^8 dyne cm or 1.17 kilogram-meters for this single pole and roughly four times this for four poles. Expressing T' in kilogram-meters and ω' in rpm, equation 29 becomes

$$T'=\frac{0.00785\omega'}{(1+0.0000047\omega'^2)^2}\text{kg-m}$$

This formula is plotted in Figure 6. A comparison of Figure 5 with Figure 6 indicates that our formula gives too rapid a falling off in torque at high speeds. It should be pointed out that other conditions, such as the degree of saturation of the iron in the magnet will upset the assumed relation between magnetomotive force and Φ and may modify equations 28, 29, 30, and 31 considerably.

The methods given in this paper may be extended to any number of poles by the method used for two and to other than circular faces. Several such calculations have been carried out, but it is doubtful if the additional theoretical accuracy justifies publishing them. The difference between the ideal boundary conditions used here and those found in apparatus is such that we recommend that the torque for one pole be calculated by equation 22 for permanent magnets or by equation 29 for electromagnets, and the result multiplied by the number of poles to give the total torque. In power apparatus the heating of the disk will change its resistivity and may cause it to expand and buckle and otherwise upset the calculations.

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Poles and Pole Treatment

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TO write about poles and the preservative treatment of poles today is like writing the review of a very successful play that has been running a long time. The players are not men, but inanimate poles. The natural backdrop is the forest. The stage is as broad as the United States and the setting is a criss-cross of thousands of miles of utility and communication lines. The engineers of these lines are the producers and directors of the play; and it is they who assign the parts to the various actors and write a changing script as the play progresses. It is the purpose of this paper to present certain highlights of the more important scenes, such as pole use and the drain on the forest, pole manufacture and treatment under standard specifications, and pole strength, and to discuss some possible rearrangements in the setting that may become necessary.

An Outline of the Pole Problem

In the forest are standing trees of various diameters and heights, some of which become poles. There are broad-leaved trees called hardwoods, and needle-leaved trees or conifers, called softwoods. In any tree there is a central core of more or less durable, nonliving wood known as the heartwood, which is surrounded by a layer of living wood known as the sapwood. There are durable woods in both the hardwood and softwood groups. The durable woods have relatively large heartwood cores and relatively thin sapwood; and the nondurable woods, on the other hand, are likely to have relatively thick sapwood.

The history of change in practice that has taken place since the first chestnut lines were built is a story of the shift from naturally durable woods to nondurable woods, and this change has involved the introduction and use of preservative materials to give the nondurable woods an economic service life.

One of the most important reasons for the shift was a national disaster in the form of the chestnut blight disease which has wiped out completely the commercial chestnut forests of the United States.

At the same time the supply of northern cedar became inadequate, at least as far as the sizes required for joint use were concerned. The question of selecting proper pole size became more and more important. The growth of the electrical industry had not followed a simple pattern, and the need for correlation of ideas and a rational standardization of pole practice led to the writing and acceptance of the American Standard Specifications for Wood Poles.[1] These specifications have had a most important influence on modern pole production. They were written around the natural poles of the forest; and they were designed to make suitable species interchangeable and to encourage the use of the greatest possible number of pole-size trees.

Other specifications had to be written or rewritten to cover the preservative treatment. The writers of these specifications focussed their attention on the finished pole, leaving only so much of process control in the specifications as was necessary to protect the timber from injury. This focussing generally took the form of defining acceptable limits for penetration. Practically speaking, the only universally accepted preservative was coal tar creosote. One major objective only was held in view in the preservation processes, namely, to fill the nondurable sapwood, whether it was very thin as in chestnut, or whether it made up 95 per cent of the pole as in many southern pines, with enough toxic creosote to prevent the growth of wood-destroying fungi.

Pole Use

Figure 1 is a copy of an old map made about the turn of the century to show the economic limits for the distribution within the Bell system of certain pole timbers. For the greater part of the country chestnut and northern cedar were favorites. In the western states western cedar was a natural selection. Creosoted southern pine had just begun to spread up from the southern pine forests, reaching as far north as St. Louis. The contrast between Figure 1 and Figure 2, which represents conditions in 1941, is striking. Chestnut is gone. The eastern scene is almost completely dominated by southern pine. Western cedar is distributed from the northwest and from the concentration yards at Minneapolis. Northern cedar is confined to parts of the New England states and the Lake states. Lodge-pole pine serves the Mountain states area. Douglas fir is being shipped from the fogbelt forests of Oregon and Washington, either directly or through Minneapolis to the eastern and southern states. The lines of distribution cross and recross in a perplexing pattern woven from preference, policy, price, and freight rates.

Many of the changes indicated in Figure 2 have been inevitable. Expansion of joint use, which has been easier since the standard pole specifications have become more widely accepted, has had a tendency to increase the length of the poles required for certain services. This has inevitably thrown the demand back on southern pine and western red cedar; and within the last two years the practical difficulties in securing large quantities of long southern-pine and western-cedar poles have practically forced the production and use of Douglas fir.

Figure 3 is a composite diagram, worked out by Doctor J. G. Segelken of the Bell Telephone Laboratories, presenting in a new fashion a picture of the relative use by the Bell system of some sizes of the pole species shown in Figure 2. Certain facts stand out plainly. One is the relative use of northern cedar and western cedar in the 30-, 35-, and 40-foot groups. Another is the major position of creosoted southern pine. A few years ago the Bell system bought between 30 and 50 per cent of all creosoted-pine poles produced in any one year. Now only about 15 per cent of the production goes into Bell system lines; but the predominance of creosoted southern pine in the Bell system use picture is a factor of major importance.

The Drain on the Forest

The degree of this importance is illustrated by Figure 4, derived from the annual reports prepared by R. K. Helphenstine, Jr.,[2] of the United States Forest Service. Piles and poles are much alike, and they come from the same forests, so that one cannot speak of a natural supply of trees for poles without taking the demand for piles into consideration.

The number of standing trees per acre in the pine forest that will make either piles or poles 35 feet or more in length is relatively small. Therefore, any increase in the demand for long poles inevitably means the working over of a larger num-

Paper 42-144, recommended by the AIEE committees on communication and power transmission and distribution for presentation at the AIEE summer convention, Chicago, Ill., June 22-26, 1942. Manuscript submitted April 13, 1942; made available for printing June 8, 1942.

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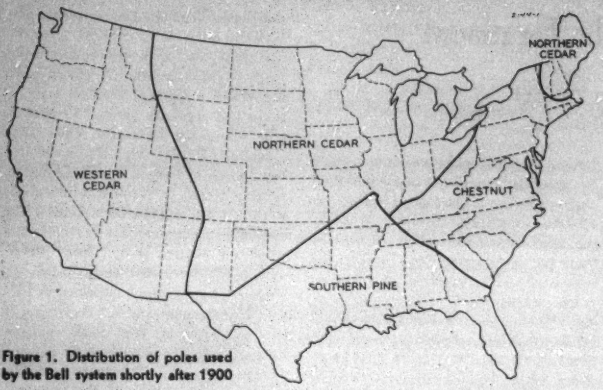

Figure 1. Distribution of poles used by the Bell system shortly after 1900

ber of acres with consequent increased labor and longer hauls. The Southern Forest Experiment Station at New Orleans conducted a unique survey in 1934–1936 which revealed that there was a more than adequate supply of pole trees of small diameter under 25 feet in length, but that the number of suitable trees in the larger sizes was relatively small. Figure 5 shows the relative use within the Bell system and outside of the Bell system for 35-, 40-, and 45-foot southern-pine poles, classes 1 to 7, American Standard. The 35-foot class 5 pole, which is a favorite for joint use makes up roughly 10 per cent of the total requirements. The relative natural occurrence in the forest of trees to make these poles is only one per cent of the total forest stand. The survey figures indicated that the number of trees suitable for 35-foot class 5 poles and for piles of about the same size taken together was approximately 3,500,000. This looks like an adequate supply. But approximately 23 per cent of the poles required for use outside of the Bell system are for 35-foot poles of smaller diameter, and the heavy demand for 30-foot class 6 and class 7 poles for cross-country lines and rural extensions during the last few years has meant cutting trees which, had they been left standing, might have furnished an entirely satisfactory supply of 35-foot poles at some later date.

The current requirements for 35- and 40-foot southern-pine poles are relatively much in excess of the occurrence of standing trees. The rapid expansion of the pulp and paper industry in the southern states and the heavy emergency demand for southern-pine lumber and piles have probably changed the relative proportions of the various sizes of standing trees since the survey. If the demand for creosoted-southern-pine poles 35 feet and longer were to continue at the present rate, a situation would soon develop in which these poles would be at a premium, and rigid straightness requirements would have to be relaxed in order to facilitate production. It would seem to be the better part of wisdom to use as many sizes as possible and to broaden the use of species to include western-cedar and Douglas-fir poles whenever it is practicable to do so.

Pole Manufacture and Standard Framing

Since the establishment of standard dimensions for the different species, there has been a definite trend toward greater mechanization in pole production. The most evident result of this trend is the pole-shaving machine for removing inner bark and smoothing the pole surface. Under Bell system specifications southern-pine poles are now trimmed by approved machine, and the trimming is limited so that the average size of the poles shall not fall below certain minimum circumferences at six feet from the butt, at mid-point, and at the top. The shaving machines are finding their way into the cedar industry, and western cedar is shaved to facilitate preservative treatment or to reduce the sapwood thickness so that it will not hold enough moisture to support decay. Machine trimming has improved the appearance of the southern-pine pole by removing the natural bumps at the knots, and by reducing the exudation of creosote, or "bleeding," from the pole surface. It also accelerates drying and facilitates production-line operation.

Generally speaking, the majority of the southern-pine poles manufactured for Bell system use are manufactured and framed to a standard pattern. At present the roof is cut square with the pole axis, and instead of the individual mortises for the crossarms, a slab gain is provided by machining a flat surface on the appropriate side of the upper part of the pole. The slab-gained pole is an economical all-purpose pole that takes the place of the mortise-gained pole, cable pole, guy stub, and push brace. There are, of course, cases in which special framing may be necessary or desirable; but special framing is a kind of custom job, and unless production orders are placed well in advance, it generally happens that specially framed poles must be produced on order.

The acceptance of standard framing has met with less resistance in southern pine than in western cedar. It is only within the last few years that the concept of a standard finished western-cedar pole has begun to take form. In the case of southern pine the principle of complete manufacture before treatment was established as a practically universal procedure before

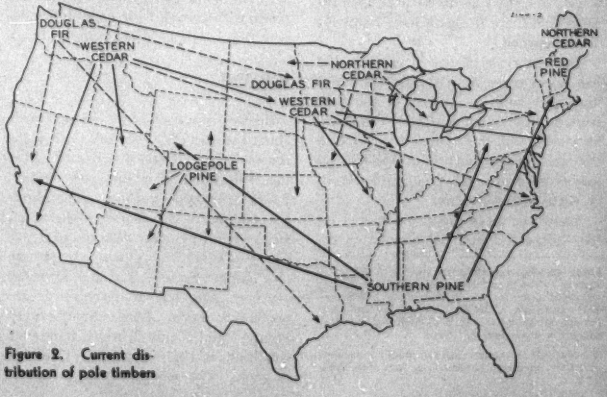

Figure 2. Current distribution of pole timbers

the creosoted-pine pole began to be accepted as a regular piece of line equipment, and the development of standard framing followed more or less naturally. In all cases gaining and boring the bolt holes is permitted after treatment in southern pine if the sapwood is 100 per cent penetrated.

Pole Preservation

The main purpose of pole preservation is to protect the nondurable sapwood from decay. The principles are relatively simple. A toxic substance is put into the wood in sufficient quantity to make the wood unpalatable to the wood-destroying fungi that cause decay. The addition of the toxic substance must be accomplished without material damage to the wood itself.

The preservative most in favor is coal tar creosote. The wood is impregnated by soaking the pole butts in open tanks or by applying pressure to the whole pole in closed cylinders. The butt-treating method has been applied with greatest success to the naturally durable thin sapwood species like chestnut and cedar, the aim being to put a protective layer of sapwood saturated with creosote around the naturally durable heart. In the case of cedar it is necessary to puncture the sapwood to secure satisfactory penetration. The open-tank method has also been used for the treatment of the thicker sapwood of lodge-pole pine, and it is now being employed as a supplementary process to the butts of poles that have been given a full-length treatment with a preservative salt.

Current treating specifications for full-length pressure treatment place the emphasis upon the product. Penetration is relatively more important than quantity of preservative retained. The Bell system, after some years of observation and experimentation, now specifies that the treatment of southern pine shall be by an empty-cell process, that the penetration shall be at least $2^1/_2$ inches unless 85 per cent of the sapwood is penetrated, and that the net retention shall average eight pounds of creosote per cubic foot of wood. Detailed discussion of the development of these requirements may be found in the *Proceedings* of the American Wood-Preservers' Association. The double requirement, based on both depth and per cent of sapwood penetrated, is necessary, because the sapwood thickness varies in poles of different lengths and circumferences.

A relatively low-residue creosote has been specified, defined by limiting the residue that remains after distillation has been carried to 355 degrees centigrade. Much of this low-residue creosote has been imported. At present such importation has practically ceased, and some adjustments are in order. The purpose of the low-residue creosote requirement was to make the product as acceptable as pos-

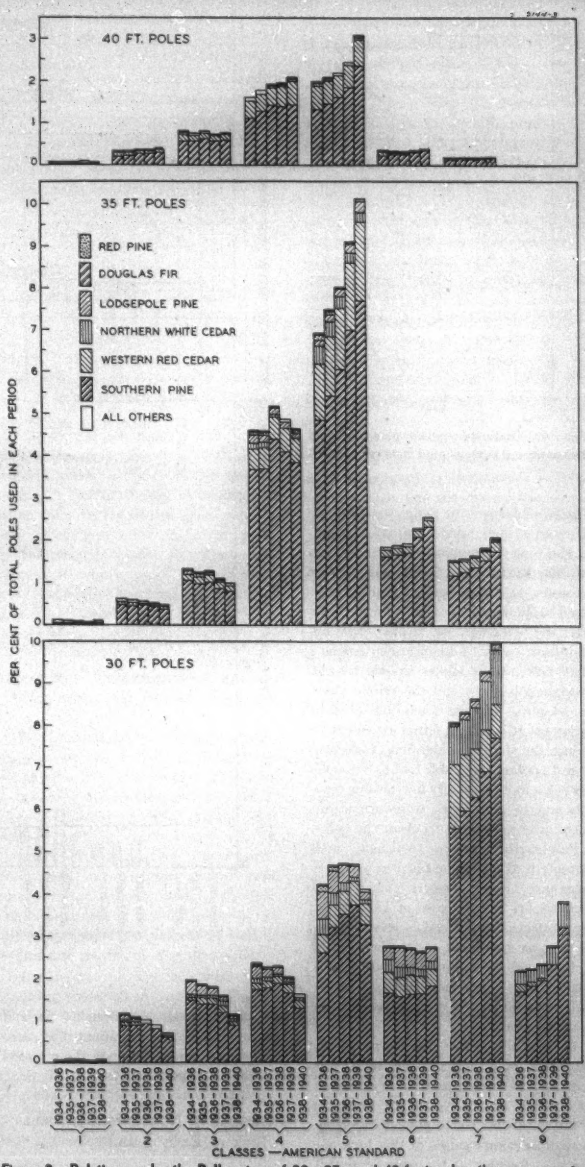

Figure 3. Relative use by the Bell system of 30-, 35-, and 40-foot poles, three-year moving averages

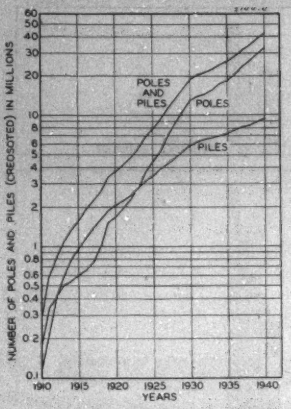

Figure 4. Creosoted-southern-pine poles and piles produced in the United States since 1910

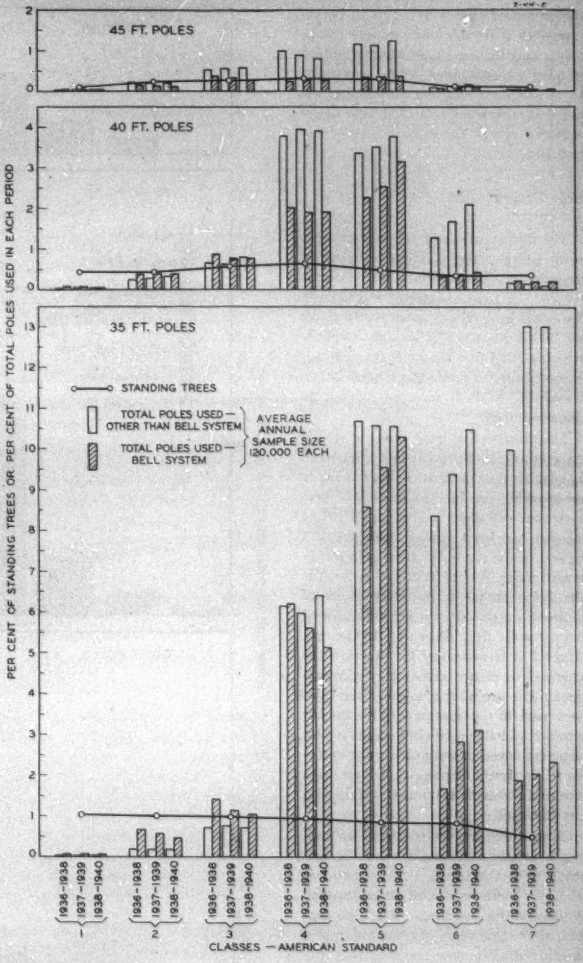
45 FT. POLES
40 FT. POLES
35 FT. POLES
PER CENT OF STANDING TREES OR PER CENT OF TOTAL POLES USED IN EACH PERIOD
STANDING TREES
TOTAL POLES USED — OTHER THAN BELL SYSTEM
TOTAL POLES USED — BELL SYSTEM
AVERAGE ANNUAL SAMPLE SIZE 120,000 EACH
1936-1938
1937-1939
1938-1940
CLASSES — AMERICAN STANDARD

Figure 5. Forest supply and use in and outside the Bell system of 35-, 40-, and 45-foot southern-pine poles

sible to all parts of the Bell system and for all types of lines, whether urban or rural. At the time the requirement was written into the specification, the heavier residue creosotes available had a tendency to bleed badly, that is, to ooze from the poles after the poles were set in line, often for months or years. A black sticky pole is a dirty pole, and it makes trouble for the construction crews and the public alike. In adapting the creosoted-pine pole to urban use it has been found expedient to reduce the standard retention of creosote from 12 pounds per cubic foot to 8 pounds per cubic foot, to specify low-residue creosote and, in some cases, to require steam baths after treatment to clean the poles.

Full-length pressure treatment with creosote is also being applied to red pine, lodge-pole pine, western cedar and Douglas fir. In the case of Douglas fir the treatment usually takes several times as long as treatment of southern pine, and although the sapwood of Douglas fir is thinner, it is sometimes hard to treat as high a proportion of the sapwood as in southern pine.

In expanding the use of red pine, lodge-pole pine, and Douglas fir, it was necessary to focus attention on adequate penetration and to reduce the retention as far as practicable to prevent bleeding. In making compromises of this type one is forced to sidestep the main argument that has been so often advanced, that the reduction of retention from 12 pounds to 8 pounds in southern pine, for example, might mean inadequate service in line. The compromises appear to be working out fairly well, and, as a matter of fact, the actual concentration in the thinner sapwoods of Douglas fir and lodge-pole pine are at about the same level as the concentration in the sapwood of southern pine.

Penetration, Nonconformity, and Risk of Early Failure

Only in the case of southern pine has the evidence on the practicability of the penetration and retention requirements been fairly well established. The latest available information on southern-pine treatment by an eight-pound empty cell process is illustrated by Figure 6, which shows the smooth distribution of 17,556 poles, nonconforming for penetration, representing approximately 3.5 per cent out of a total sample of 525,000 produced in 1941. The distribution has been divided into nonconformity zones, numbered 1 to 5. The interpretation of the distribution is illustrated in Table I. From studies of the behavior of creosoted southern-pine poles in line[3,4], certain failure factors have been determined which

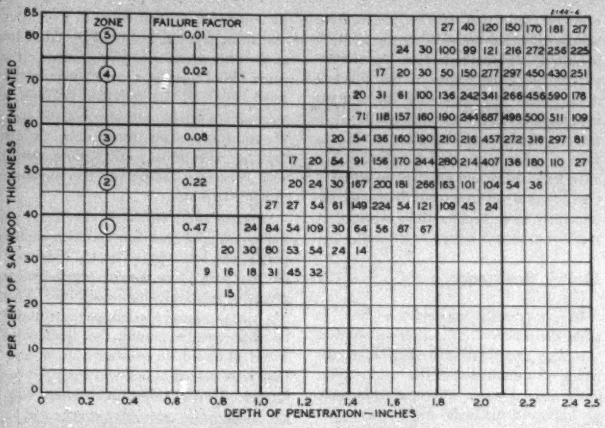

Figure 6. Distribution of southern-pine poles nonconforming for creosote penetration, 1941 production, arranged in nonconformity zones according to risk of early failure in line

are applicable to the percentage of poles in the respective nonconformity zones. These failure factors may be defined as the percentage of the poles within these zones which may be expected to fail within 15 years of installation. Recent experience indicates that these failure factors are probably high. It appears likely that the total risk of early failure in a group of poles like those under consideration is less than the estimated 0.128 per cent. The method of interpretation illustrated was first advanced several years ago, and up to the present no reason has been brought forward for changing it. Broadly, it means that poles which meet the penetration requirements of current standard specifications should have an entirely adequate service life.

Green Salt Treatment

A new preservative for this country, called green salt, a mixture of five parts potassium dichromate, three parts copper sulphate, and one part arsenic acid, in a cold water solution, has been used recently for the commercial treatment of seasoned southern-pine poles. The treating solution contains about seven per cent of the salts. The penetration has averaged about 98.5 per cent of the depth of the sapwood, which is better than the average generally obtained in creosote treatments; and the number of nonconforming poles was approximately three per cent. The distribution of nonconformity appears to be of the same order as that shown in Figure 6, with fewer poles in zones 1 and 2. The finished product is cleaner, lighter in weight, and stiffer than the creosoted pole, and the outer fibers are somewhat harder, making the green salt poles somewhat more difficult to climb than the creosoted pole. Generally speaking, the reaction of the field forces to the new poles has been excellent.

Immersion Treatments—Creosote, Petroleum, and Pentachlorphenol

The virtual shutting off of creosote importation by the war has stimulated the use of other types of preservatives such as mixtures of creosote and petroleum, with or without the addition of some other material such as pentachlorphenol; or the use of a five per cent solution of pentachlorphenol in petroleum alone.[8] The latter solution is being used for the full-length treatment of western cedar by an open-tank immersion process as well as for pressure treatment of southern pine.

Machine-shaved western cedar poles are being creosoted by immersion in hot creosote, followed by the usual butt treatment. The end in view in these western cedar treatments is to produce poles in which the hazard to linemen from sapwood decay will be eliminated.

Salt-Creosote Poles

During the last 15 years approximately 800,000 southern-pine poles treated with zinc meta arsenite have been placed in line. The majority of them have been purchased and set by power and light utilities. The deterioration that has occurred in these poles has happened at or below the ground line and, in most cases, the reduction in circumference at that point has taken place slowly. Above ground line the condition of the poles is excellent. To prevent the deterioration at the ground line, poles that are treated full length with zinc meta arsenite are now being given a butt treatment with creosote. Specifications for this double treatment call for a penetration in the above ground part of the pole of $2\frac{1}{2}$ inches unless 85 per cent of the sapwood is penetrated, as in the case of creosoted southern pine. Below ground a full sapwood penetration of creosote is not required. The aim of the specification is to provide for adequate protection of the butt without the use of too much creosote. This salt-creosote pole is being distributed in the northeastern states on the bases of strength and life expectancy equivalent to creosoted southern pine. Other salts than zinc meta arsenite, such as those covered by the current Federal specifications for use in treatment of timber not in contact with the ground, are under consideration. It is interesting to note in this connection that double treatment using zinc chloride followed by a creosote butt treatment was in use in Texas prior to 1910. Some of the poles of this vintage have given at least 34 years' service in line and are still good.

Conditioning Poles for Treatment

This brief discussion of preservation cannot be dropped without some mention of the problem of preparing poles for treatment. In theory at least, it would be desirable to dry poles of all species before treating them. Practically speaking, it is almost impossible, except at certain seasons of the year, to air-season southern-pine poles for either creosote or salt treatments without great risk of the poles becoming infected with molds and strength-reducing fungi during the process. The larger the pole, the harder it is to dry it. Charges of either green or dry poles may be treated satisfactorily with

Table 1. Southern-Pine Poles—1941 Production—Estimate of Risk of Early Failure in Line

Nonconformity zone	Number of Poles	Per Cent of Total Poles	Failure Factor	Risk of Early Failure Per Cent of Total Poles
1	132	0.025	0.47	0.012
2	839	0.160	0.22	0.035
3	2,862	0.545	0.08	0.044
4	5,432	1.035	0.02	0.021
5	8,291	1.579	0.01	0.016
	17,556	3.344		0.128

due care in the control of the treating process. Partially seasoned poles, either alone or in mixture with seasoned or green poles, may make the treating results very variable. The Bell system specification requires steam conditioning for at least six hours at 259 degrees Fahrenheit before impregnation with creosote, in order to smooth out some of the variables and to sterilize the wood.

To prevent deterioration during seasoning, some producers follow the practice of pretreating all pole stocks as soon as they have dried down to the point where such treatment can be given economically with approximately four pounds of creosote per cubic foot. The poles are then stacked in the yard and held for orders. The additional poundage required to meet the minimum retention specified is added by a second treatment. In other cases the poles are treated under pressure with weak solutions of preservative salts.

The kiln-drying of southern-pine poles[6] has been carried far enough experimentally during the last few years to show that it is a distinctly promising method of preparing the poles for treatment. Ironically enough, it begins to look as if the creosoted kiln-dried poles would have to be steamed for a short period at the end of the creosoting process in order to clean them and prevent subsequent bleeding of the creosote from the pole surface.

In the case of certain of the salt preservatives organic matter in the green or partially seasoned pole causes a very rapid chemical reduction of the preservative solution if either the wood or the solution is heated; and this reduction does not occur to the same degree if the wood is dried before treatment, and the solution is applied cold. In any event a dry pole treats quickly, and the plant is able to save cylinder hours, and a pole that has once been dried and then given either a creosote or a salt treatment dries out subsequently more rapidly than a pole that was not seasoned before treatment.

Electric Resistance

It is extremely important to bear in mind the practical difficulties involved in seasoning and treating timber before entering on a discussion of the conductivity of the treated wood. Measurements made by improved methods[7] confirm the generally accepted conclusion that the electric resistance varies inversely as the moisture content. There is a temperature factor, but it can be more or less ignored if the measurements are made within certain temperature limits. It is not so easy to control moisture content. The moisture may come from two sources, that is, it may be the moisture that is left in the sap that was in the tree when it was felled, and it may be moisture absorbed from rain or melting snow as the pole is lying in a concentration yard or standing in line.

The sapwood of a green pole may contain more water than its own dry weight. At a moisture content equal to 27–30 per cent of its dry weight, wood is said to be at the fiber saturation point, that is, at a point where there is no free water in the wood cells. If the moisture content is above this fiber saturation point, the electric resistance of the wood is low. Below the fiber saturation point electric resistance increases sharply as the moisture content decreases.

Suppose that, either as the result of well-considered seasoning practice on the part of the producer, or on the insistence on the part of a possible customer, a group of relatively high-resistance poles has been produced and shipped. It would be quite wrong to assume that these poles would all have high resistance at the time they were placed in line and equipped for service. During shipment moisture may get into the open seasoning checks and be absorbed by the inner sapwood and untreated heartwood of the pole. Or the poles may be exposed to rain and snow for months before they are erected. In fact, any method of open flat storage previous to line use is almost certain to bring about a great variation in the resistance of poles that may have started out on a relatively high resistance level. Even the best of storage conditions, under cover or in vertical piles, is no guarantee of high resistance of the pole in line. Driving rains, sleet, or snow storms may wet the windward side of the pole and bring it to practical saturation during the course of a storm. The character of the preservative itself simply adds another variable to these general conditions over which very little control can be exercised.

Aside from drying a pole properly before treatment so that it will dry out more quickly after treatment, there is little that can be done in writing specifications, or in actually producing poles, that will make it possible to turn out high resistance units; and after the poles have once been produced, each stick becomes an independent variable in its resistance characteristics. In practical operation, therefore, no pole can have a high resistance all the time.

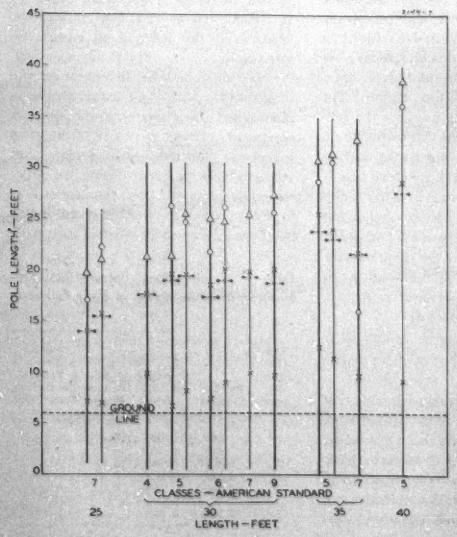

Figure 7. Independence of maximum knots and points of break in southern-pine poles and pole-top sections

Δ Maximum group of knots in any 12-inch section

o Maximum single knot

o---o Ground line for test of top section

x Point of break

—Creosoted poles

—Green salt poles

When only Δ is shown, the maximum single knot is in the maximum group

The upper x shows location of point of break in top section

Pole Strength

In writing the American Standard Specifications for Wood Poles,[1] all of the species were dimensioned so that they would have approximately equal resisting moments at the ground-line for any given class and length. These strength requirements have been translated into what may be called standard breaking loads starting at 1,200 pounds for class 7 and running to 4,500 pounds

Table II. Southern-Pine Poles—Breaking Test Data

No.	American Standard Class	American Standard Length	Average Diameters in Inches: Maximum Single Knots	Average Diameters in Inches: Maximum Knot Groups	Whole Pole Relative Average: Breaking Load*	Whole Pole Relative Average: Modulus of Rupture**	Top Section Relative Average: Breaking Load*	Top Section Relative Average: Modulus of Rupture**
Creosoted Poles								
1	4	30	1.2	1.8	122	119	178	117
4	5	30	1.7	3.8	118	103	156	101
3	5	35	1.1	3.9	150	130	192	118
5	6	30	1.6	5.0	112	99	127	80
5	7	25	1.5	4.9	116	104	140	96
1	7	35	1.9	5.2	127	124	175	133
3	9	30	1.6	4.8	†	120	†	140
—	—	—	—	—	—	—	—	—
22			1.5	4.5	122	110	152	105
Green Salt Poles								
3	5	30	2.2	4.1	150	129	205	107
8	5	35	1.6	3.5	146	127	182	104
2	5	40	1.4	2.7	138	130	223	119
38	6	30	1.7	4.5	121	104	151	99
11	7	25	1.2	3.7	149	135	189	119
8	7	30	1.5	3.9	148	129	170	94
—	—	—	—	—	—	—	—	—
70			1.6	4.1	133	116	167	103
—	—	—	—	—	—	—	—	—
92			1.6	4.2	100‡	100‡	125	90

* The standard breaking loads were taken as 100 in each case. These standard loads are: class 4—2,400 pounds; class 5—1,900 pounds; class 6—1,500 pounds, and class 7—1,200 pounds.

** The standard ultimate fiber stress for creosoted-southern-pine poles—7,400 pounds per square inch—was taken as 100 in each case.

† No standard breaking load for class 9 has been established. For the three poles listed the average breaking loads for the poles and for the pole-top sections were 1,317 pounds and 1,840 pounds, respectively.

‡ The averages for the whole poles were taken as 100 for comparison with the top sections.

for class 1, approximately on a 25 per cent geometric progression.

Three years ago R. C. Eggleston of the Bell Telephone Laboratories began a series of breaking tests on machine-shaved southern pine treated with creosote, and with green salt. A novel scheme was introduced. The top sections of the poles as well as the poles as a whole, have been tested whenever possible. The results of part of these tests, on 92 poles and pole-top sections, are summarized in Table II. The poles averaged well above their rated class breaking loads, above the American Standard fiber stress—7,400 pounds per square inch—and within the expected variation for modulus of rupture. The modulus of rupture of the pole-top sections averaged 90 per cent of the modulus of rupture of the poles as a whole. The top sections of the poles were broken with short lever arms and, in spite of lower modulus of rupture, were on the average still sufficiently strong to meet their specified pole-class breaking load.

The position of the maximum knot and the maximum-knot group in relation to the point of break for the poles as a whole and for the pole-top sections are shown in Figure 7. Each line in the figure represents one of the groups defined by columns 1, 2, and 3 in Table II, and within given class length groups the creosoted-pole and the green-salt-pole diagrams are placed side by side to facilitate comparison. The independence of maximum knot position and break position is obvious. Only the pole-top sections, which had to be clamped in the holding device to represent the point of guying, broke at conspicuous knot groups. In some instances the very first point of break seemed to be at small knots an inch or less in diameter or even in hidden knots which did not appear on the surface of the poles at all. Occasionally poles will break during unloading. Apparently, such breakage is the result of impact shock far in excess of what the poles could stand. Generally, this impact shock comes from dropping the pole or from catching it between others as it is rolled off the car or trailer. The breaking in such cases at knot groups is coincidental with the shock and point of application and does not indicate dangerous weakness in the pole itself.

Ground-Line Treatment

One other subject remains for brief mention, namely the prolongation of the life of the existing pole plant. The evidence from test plot experiments and observation of poles in service indicates that some sort of ground-line treatment should be applied to untreated poles that are worth saving at the time of inspection, as a part of the regular inspection procedure. When one looks back over the years, it appears that the mistake, if any, that was made in earlier ground-line treatments was not in the treatment itself, but rather in the assumption that a single application would be effective for the life of the pole. The methods now recommended are the Osmose process or the simplified procedure that consists of the regular inspection and excavation, and treatment with a water-soluble salt and creosote. Originally a pound of sodium fluoride was dumped into the excavation around the pole, and the hole lightly backfilled. Then, after making a narrow V-shape trench against the pole, about one gallon of cold creosote was poured into the hole by letting it run against the pole, at a height of about 12 inches above the ground line, from the flattened spout of a watering can. The backfill was then finisfied, leaving the earth around the ground line fairly saturated with creosote and leaving a water-soluble salt to be taken up by the moisture in the wood. Sodium fluoride has been replaced in part by borax in the general plan as a result of the shortage of the former salt. The protection afforded by such a treatment seems to be good for about five years.

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Interim Report on Guides for Overloading Transformers and Voltage Regulators

AIEE COMMITTEE ON ELECTRICAL MACHINERY
Transformer Subcommittee*

THE present war emergency has crystallized the need for additional information concerning the maximum load capability of modern-design transformers and voltage regulators in order that these apparatus may be utilized to a greater extent for meeting present and new load requirements with a minimum amount of new equipment, thus conserving critical war materials. It will be noted that the papers[1-3] presented at the AIEE convention June 24, 1942 give somewhat divergent views on permissible overloads and on the effect of temperature on transformer insulation.

The relation between the life expectancy of insulation as indicated by laboratory tests and the actual life of a transformer is largely theoretical, so that the use of such information must be tempered by sound judgment based on operating experience. This report represents a compromise of views that is considered conservative and satisfactory for immediate general use, subject to the limitations and cautions given herein.

Consideration is given to operation with normal life expectancy and also with moderate sacrifice in life expectancy, thus taking into account the effect of the following factors:

(*a*). Characteristics and limitations of the apparatus involved.

(*b*). Ambient temperature.

(*c*). Load factor.

(*d*). Supplemental cooling.

(*e*). Sacrifice of life expectancy.

Normal Life Expectancy

In this report normal life expectancy is based on continuous operation at rated load with a daily average ambient temperature of 30 degrees centigrade for self-cooled or forced-air-cooled transformers, 25 degrees centigrade for water-cooled transformers, and other usual service conditions as given in American Standard *C*-57, Section 2.000. The "Guides for Operation of Transformers" included in American Standard *C*-57 give general recommendations for the loading of oil-immersed transformers and voltage regulators for recurrent and emergency overloads with small effect on normal life expectancy, while this report will supply, in addition to other information, data for heavier overloads with moderate sacrifice of life expectancy.

Loading for Normal Life Expectancy

The maximum load capability is determined to a considerable extent by the type and the electrical characteristics of the specific piece of apparatus. However, some general guides may be set up, based upon the more usual comparatively modern design characteristics, and with provision for taking into account the factors of temperature of the cooling medium, load factor, thermal ability of bushings and accessories, expansion of oil due to temperature increase, possible pressure in sealed transformers, method of cooling, and so forth.

Design Characteristics

The general information on transformer loading in this report applies to the comparatively modern-design transformers built since about 1928. The information will not apply in the usual case to the older-design apparatus without consideration of the design characteristics of each piece of apparatus.

Ambient Temperature

For low ambient temperatures the continuous kilovolt-ampere loading may be increased one per cent for each degree that the daily average temperature is below 30 degrees centigrade for self-cooled transformers, three fourths of one per cent for each degree below 30 degrees centigrade for forced-air-cooled transformers, and one per cent for each degree below 25 degrees centigrade for water-cooled transformers.[4] Similarly, the loading should be decreased two per cent for each degree that the daily average ambient is above these temperatures. For continuous loading these rules result in normal life expectancy, the same as for operation at rated load with ambient temperatures of 30 degrees centigrade and 25 degrees centigrade respectively. Detailed applications of these rules are given in the American Standard *C*-57, "Guides for Operation of Transformers."

Under some conditions greater permissible overload capability can be obtained by using "equivalent annual ambient" instead of the daily average ambient when applying the rule for overloads due to change in ambient. The equivalent annual ambient is the temperature which, if maintained constantly, would result in the same aging as that occurring under the actual ambient temperature throughout the year. This matter is being given further consideration.

Load Factor

For daily load factors below 100 per cent the loading may be increased 0.3 per cent for each per cent that the daily load factor is below 100 per cent,[5] with normal life expectancy. More nearly accurate corrections based on an actual load curve are not usually justified for normal loading. In no case should the overload permitted by this factor exceed 15 per cent, corresponding to 50 per cent daily load factor.

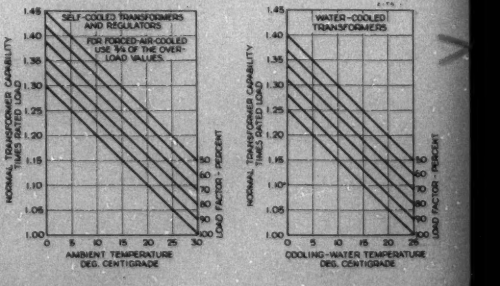

SELF-COOLED TRANSFORMERS AND REGULATORS
FOR FORCED-AIR-COOLED USE ¾ OF THE OVERLOAD VALUES
NORMAL TRANSFORMER CAPABILITY TIMES RATED LOAD
LOAD FACTOR - PERCENT
AMBIENT TEMPERATURE DEG. CENTIGRADE
WATER-COOLED TRANSFORMERS
COOLING-WATER TEMPERATURE DEG. CENTIGRADE

Figure 1. Transformer and regulator capabilities for normal life expectancy

Paper 42-156, recommended by the AIEE committee on electrical machinery for presentation at the AIEE summer convention, Chicago, Ill., June 22-26, 1942 and at the AIEE Pacific Coast convention, Vancouver, B. C., Canada, September 9-11, 1942. Manuscript submitted June 29, 1942; made available for printing July 9, 1942.

* Personnel of AIEE transformer subcommittee: M. S. Oldacre, chairman; F. S. Brown, E. S. Bundy, J. E. Clem, I. W. Gross, V. M. Montsinger, J. R. North, W. C. Sealey, P. J. Vogel, C. F. Wagner.

Acknowledgment is made of the assistance given by R. T. Henry, H. W. Hartzell, J. S. Lennox, and D. L. Levine.

Temperature Rise of Windings

The information in this report is based on apparatus designed for the standard 55 degrees centigrade rise. If a transformer has been designed for other than 55 degrees centigrade rise, a rating to give 55 degrees centigrade rise can be calculated, and then the correction factors stated herein can be applied.

Supplemental Cooling—Existing Transformers

The load that can be carried on existing transformers can be increased by adding auxiliary cooling equipment such as radiator fans, external forced oil coolers, or water spray equipment. The amount of additional loading that such devices permit varies widely depending on

(*a*). Design characteristics of the transformer.

(*b*). Type of cooling equipment.

(*c*). Permissible increase in voltage regulation.

(*d*). Limitations of associated equipment.

Specific data should be obtained for each individual transformer.

When applying supplemental cooling to existing transformers, the permissible overloads should be based on the hottest-spot temperature rise instead of on average winding temperature rise. Usually the hottest-spot temperature rise over top oil temperature increases as the 1.6 power of the load.

If it is found that the bushings, leads, or other accessories are not a limiting feature, oil-insulated self-cooled transformers by the addition of fans may have the output increased in many cases 25 per cent and in some cases up to 33 per cent. Similarly, the addition of external forced oil cooling to oil-insulated self-cooled or oil-insulated water-cooled transformers may increase the output in many cases 25 per cent and in some cases up to possibly 66⅔ per cent.

Water-spray equipment may be used in some cases as an emergency method of additional cooling. It is not generally considered satisfactory as a means of obtaining continuous additional capacity or for year-round operation. The added capacity obtainable by the use of water spray on oil-insulated self-cooled transformers is dependent on the air and water temperature, humidity, design of bushings, leads, and other accessories of the transformer. The water spray equipment may increase the capacity in many cases 25 per cent and in some cases up to possibly 60 per cent.

Figure 2. Emergency load capability of self-cooled transformers larger than 500 kva

See text for cautions and limitations

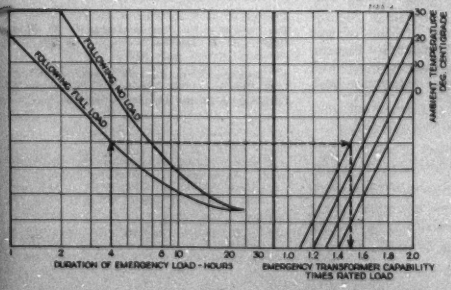
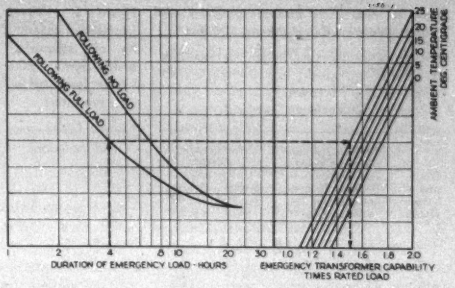

FOLLOWING NO LOAD
FOLLOWING FULL LOAD
DURATION OF EMERGENCY LOAD - HOURS
EMERGENCY TRANSFORMER CAPABILITY TIMES RATED LOAD
AMBIENT TEMPERATURE DEG. CENTIGRADE

Figure 3. Emergency load capability of water-cooled transformers larger than 500 kva

See text for cautions and limitations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DURATION OF EMERGENCY LOAD - HOURS
EMERGENCY TRANSFORMER CAPABILITY TIMES RATED LOAD
AMBIENT TEMPERATURE DEG. CENTIGRADE

Emergency Loading With Moderate Sacrifice of Life Expectancy

The foregoing discussions have dealt with loading of transformers on the basis of normal life expectancies. In this section loading with moderate sacrifice of life expectancy during infrequent emergencies to values above those given in the American Standard *C*-57 "Guides for Operations of Transformers" is discussed.

On the basis of available data it is reasonable to consider that hottest-spot temperatures for durations shown in Table I represent an average sacrifice of life with each such emergency operation of not more than one per cent of the normal life expectancy as determined by the tensile strength of the winding insulation.

Table I. Temperatures for Short-Time Emergency Loads With Moderate Loss of Life of Insulation

Duration of Load—Hours	Hottest-Spot Temperature—Degrees Centigrade
1	137
2	130
4	125
8	120
24	110

With the above temperature limits and where specific data on the individual transformer are not available, the following loads are considered satisfactory for modern transformers and regulators with average ambient temperature during the overload period of 30 degrees centigrade for self-cooled and forced-air-cooled transformers and a water temperature of 25 degrees centigrade for water-cooled transformers. These overload values apply to the normal continuous name-plate kilovolt-ampere rating for output voltages equal to or above name-plate rating, and

Figure 4. Emergency load capability of forced air-cooled transformers larger than 500 kva

See text for cautions and limitations

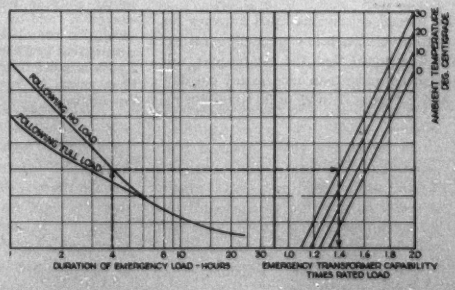
FOLLOWING NO LOAD
FOLLOWING FULL LOAD
DURATION OF EMERGENCY LOAD - HOURS
EMERGENCY TRANSFORMER CAPABILITY TIMES RATED LOAD
AMBIENT TEMPERATURE DEG. CENTIGRADE

Table II. Short-Time Emergency Overloads for Transformers Rated Above 500 Kva*

(See text for cautions and limitations regarding ambients, rating, number of overloads, and so forth)

(Times Rated Load)

Duration of Load—Hours	Self-Cooled and Water-Cooled		Forced-Air-Cooled	
	Following Full Load	Following No Load**	Following Full Load	Following No Load**
1	1.9	2.0†	1.6	1.8
2	1.7	2.0	1.45	1.6
4	1.5	1.7	1.35	1.4
8	1.35	1.45	1.25	1.25
24	1.25	1.25	1.15	1.15

* Special consideration should be given to installations involving exceptional heavy-current designs.

** Values for operation "Following No Load" are on the basis that the transformer has been excited for at least several hours' time prior to application of the load. The loads that can be carried following partial load can be determined with sufficient accuracy by direct interpolation.

† It is considered that two times rated load is the maximum that should be carried, regardless of time, without special consideration.

Table III. Short-Time Emergency Overloads for Transformers Rated 500 Kva and Below,* and for Regulators

(See text for cautions and limitations regarding ambients, rating, number of overloads, and so forth)

(Times Rated Load)

Duration of Load—Hours	Transformers 500 Kva and Below		Regulators	
	Following Full Load	Following No Load**	Following Full Load	Following No Load**
1	1.7	1.9	1.5‡	1.5‡
2	1.55	1.7	1.5	1.5‡
4	1.4	1.5	1.4	1.5
8	1.3	1.35	1.3	1.35
24	1.2	1.2	1.2	1.2

* Special consideration should be given to installations involving exceptional heavy-current designs.

** Values for operation "Following No Load" are on the basis that the transformer has been excited for at least several hours' time prior to application of the load. The loads that can be carried following partial load can be determined with sufficient accuracy by direct interpolation.

‡ It is considered that 1.5 times rated load is the maximum that should be carried, regardless of time, without special consideration.

to normal continuous rated amperes for output voltages below name-plate rating. It is assumed that the emergencies will occur not more than once on any one day and not more than 25 or 30 times during the normal life of the transformer, and that the insulation, windings and oil are reasonably clean and free from excessive amounts of moisture and sludge.

Figure 5. Emergency load capability of self-cooled transformers (500 kva or less) and of regulators

See text for cautions and limitations

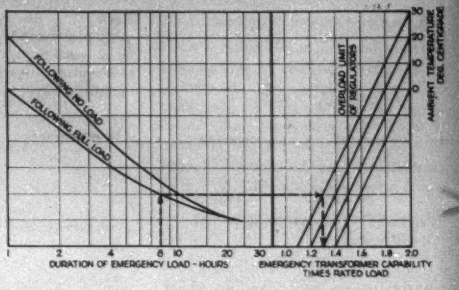

Table II shows permissible loads for infrequent emergencies for modern sealed-type transformers rated above 500 kva which have the oil effectively protected from exposure to air and moisture. Table III shows permissible loads for infrequent emergencies for modern transformers rated 500 kva and below and for modern regulators.

Conclusions

Information has been presented herein concerning the effects of the characteristics of specific apparatus, ambient temperature, load factor, supplemental cooling, and so forth, in determining the load capability of transformers and voltage regulators for both normal and emergency conditions.

The effects of these factors are cumulative, as follows:

For *normal operation* with normal life expectancy the effects of load factor, ambient temperature, and supplemental cooling may all be added in determining the load capability. Figure 1 illustrates the application of factors for ambient temperature and low load factor in determining the normal capability for transformers and regulators.

For *short-time emergency operation* with moderate sacrifice of life the effect of the actual ambient temperature during the emergency and of supplemental cooling should be considered in addition to the values given in Tables II and III. Figures 2 to 5 inclusive illustrate the application of these values to determine emergency load capabilities.

The principles and facilities described in this report may be applied to existing or proposed new equipment and should be effective in conserving critical war materials.

Caution: It must be recognized that overloads should not be applied to transformers or regulators without a thorough study of the various limitations involved. Among these limitations are oil expansion, pressure in sealed-type units, bushings, leads, soldered connections, tap-changers, and so forth, and the thermal capability of associated equipment, such as cables, reactors, circuit breakers, disconnecting switches, current transformers, and so forth. These may constitute the practical limit in load-carrying ability.

Before overloading transformers or regulators to the full extent covered in this report, it is recommended that the overload capabilities of the equipment be checked with the manufacturer.

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A Compressed-Air Operating Mechanism for Oil Circuit Breakers

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General Field of Application

THE recent trend toward better use of existing lines and power sources has brought a demand for faster operation of oil circuit breakers and further simplification of control. In the past it has been common practice to use a solenoid or motor to provide closing energy for these breakers, either of which requires a substantial battery, means for keeping it up to full charge at all times, large conductors between the battery and the breaker to handle the heavy currents which exist for approximately one second while the breaker is closing, and generously proportioned control equipment. Consequently, the cost of apparatus associated with the breaker, but actually installed apart from the breaker, becomes a significant item.

Compressed air can be used as a source of energy to close these breakers, and with several obvious advantages. In the first place, the electrical drain on a battery at the instant of closing is only the control relay current, not the full solenoid closing coil current. This may be a reduction of the order of 1 to 100 which is reflected in smaller batteries and chargers, lighter control cables, and contactors. Another advantage is that full air pressure is instantly available to start closing the breaker, whereas a solenoid builds up in power at a slower rate, depending on the inductance of the coil. Thus it is possible to secure faster breaker operations.

In a fundamental way the apparatus required for closing a breaker with compressed air consists of:

(*a*). A source of air comprising a compressor and reservoir.

(*b*). A cylinder and piston within which the air can be released to force the breaker to the closed position.

(*c*). Suitable means for controlling the flow of air by means of magnetically operated valves operated from a distant point.

Paper 42-114, recommended by the AIEE committee on protective devices for presentation at the AIEE summer convention, Chicago, Ill., June 22-26, 1942. Manuscript submitted April 20, 1942; made available for printing June 1, 1942.

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Obviously, it is not practical to build the commercial apparatus in quite such simple form, and various requirements of operation have made it desirable to add refinements as the following will disclose.

The Air Supply

It is desirable that an air reservoir be located close to each operating cylinder, as air flowing a long distance through small pipes will lose pressure to such a degree that the delivered air may not be able to accomplish the work of closing the the breaker in the required time. Hence, a 20- or 30-gallon reservoir is installed in the same housing with the operating mechanism and control and mounted on the end of the breaker.

For reliable service it has been recommended that a motor-driven compressor be mounted in each housing, thus making each breaker entirely independent of any other. It could be argued that this is an unnecessary expense where several breakers are installed in close proximity to each other, and where one compressor could perhaps handle the several reservoirs. However, it appears that most operating men look at the possible dollar saving as overbalanced by the hazard of shutting down the entire group of breakers, in case of the failure of the one compressor, and the possible difficulty of maintaining interconnecting air piping clear and tight.

If it is preferred to use a single compressor unit for an entire station, it is recommended that a double compressor be used so as to provide increased reliability. Also, proper consideration must be given to protection against mechanical damage to piping and to the drainage of any water which might condense in the air line. If freezing temperatures will be encountered in the locality of installation, adequate sizes of pipe and sumps must be provided to prevent blocking with ice.

The assembly of compressor and reservoir is built to exceed the standards required for industrial systems and railway brake installations, in which continuity of performance has been an important factor worked out years ago. It is designed to meet all usual safety code inspection requirements, and the reservoir carries the stamp of the boiler code inspector of The American Society of Mechanical Engineers. An automatic governor maintains a maximum pressure of 200 pounds per square inch, starting the compressor whenever the pressure drops to 15 pounds below the preset maximum. A safety valve limits the reservoir pressure to 225 pounds. Ordinarily only one-half or three-fourth horsepower is required in the compressor motor so that little current is drawn from the a-c supply line. In ordinary service the motor will run only a few minutes each day, as required for the occasional breaker operation and in order to overcome slight leakage loss. Starting with an empty reservoir, a full charge can be pumped in one-half hour. The motor need not run each time the breaker operates, as the amount of air used is frequently so small as not to drop the reservoir pressure to the point where the automatic governor picks up. In case of the failure of the supply voltage to the compressor motor, a full reservoir contains enough air to operate the breaker at least five times. Further, if there should be no immediate demand for an operation, it would require more than 12 hours for a normally tight air system to leak down to a dangerously low pressure, giving a wide margin of time to re-establish compressor power or service. A low-pressure switch indicates through an alarm circuit when the drop in reservoir pressure is becoming acute, and another switch locks out the closing relay circuit so as to prevent the attempt to close, when the air pressure is too low to insure completion of the operation.

The Lever System

Figure 1 shows a typical mechanism assembly mounted on the tank of a 138-kv outdoor oil circuit breaker. The compressor and reservoir occupy the space at the right of the assembly. At the left and center is the operating mechanism itself, with a magnetically operated inlet valve conveniently located directly in front of the main cylinder. The current demand of this magnet valve is well under two amperes.

One requirement for a mechanism of this type is that it shall be capable of reclosing the breaker promptly, under some conditions in not over 20 cycles (one-third second). This mechanism meets the demand by retaining a positive mechanical connection between the breaker and the operating piston at all times, so that at any time it may be desired air admitted to the cylinder will immediately act to close the breaker, regardless of

whether it may have reached the full open position or not. A single lever, hinged at one end, and carrying a roller at the other end to be held under the hook shaped latch when the breaker is closed, is attached to both the piston and the breaker pull rod at the center.

The breaker is closed under the effect of the compressed air and latched in the closed position, so that the air can be cut off at the end of this stroke. When the breaker is called upon to open, the latch is released by a trip magnet, and the usual accelerating spring on the breaker furnishes the impetus needed to secure the proper contact opening speed. The opening is therefore independent of the condition of the air supply, and required interrupting time of the breaker is controlled entirely by the mechanical time of unlatching the mechanism and accelerating the contacts by springs which were preloaded during the closing stroke of the breaker.

It is evident that when a direct mechanical connection exists between the breaker and the piston, closing and reclosing operations are easily obtained. Experience with solenoids has shown that it is necessary to provide them with mechanically trip-free linkages so as to permit full opening speed without the contacts being delayed by the magnetic drag of the closing solenoid. The mass of the solenoid core also acts as a drag to prevent full opening speed. These difficulties are not present in the air mechanism when a light piston is used, and when some means is provided for dumping from the operating cylinder, the air still under pressure, so that it will not restrict the opening speed of the contacts.[1] The latter demand is met by a series of exhaust ports—on the side wall of the main cylinder, near the fully closed position—which are opened simultaneously with the operation of the breaker trip coil. The total area of these ports is approximately four square inches, and oscillographic pressure records show that the collapse of pressure is so fast that less than 25 pounds remains in the cylinder at the time the contacts part. The extreme speed of this dump valve is secured by utilizing the high-pressure air on the end of the cylindrical valve, after it has once been cracked by a pilot piston or small magnet.

While the single-lever design adequately meets the requirements of quick reclosing, some modification is necessary where manual operation of the smaller breakers is concerned. In this class of apparatus, one man can complete the closing operation with a single quick stroke of the removable handle, but must be protected against holding the breaker in on a fault, as would be the case with the non-trip free mechanism. A solution to this problem is shown in Figure 2, where the single-lever system for power operation is modified when it is to be manually operated, by unlocking the fixed hinge point and temporarily restraining the automatic latch over its roller, so that, if necessary, the breaker can be tripped in the manner of the conventional double-lever system. Thus, the benefits of trip-free action can be secured, while in the same parts the inherently fast reclosing possibilities of the non-trip free action are retained.

Controlling the Air Flow

There is a characteristic mechanical load curve for all breakers having the general shape of that marked "Breaker Load" in Figure 3. It is made up of the dead load, balance and accelerating springs, and the extra load of contact pressure springs at the closed position. The breaker toggles may alter the magnitude of these combined loads at different parts of the stroke, but the fundamental characteristic remains. The simple solenoid pull curve is well adapted to this, since it develops a greater pull as the cores come together (see curve marked "Solenoid Mechanism" also in Figure 3). The surplus of power shown for the solenoid

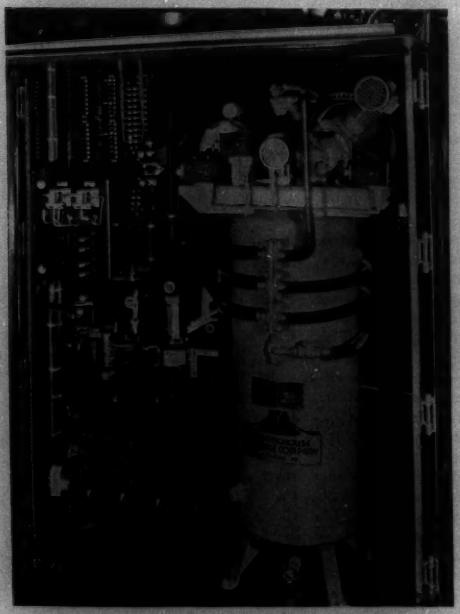


Figure 1. Type CAS-8 mechanism for outdoor service

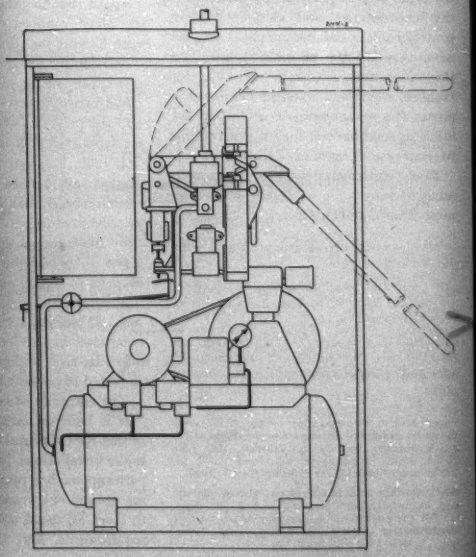


Figure 2. An outdoor-type compressed-air mechanism with trip-free hand-closing lever

goes into speed and, of course, is eventually lost, as breaker strikes its stops in the closed position, but the general shape of the pull curve of the solenoid usually falls just above the load curve of the breaker, so that there are no large instantaneous surpluses or deficiencies. With the same breaker and a simple air-operated mecha-

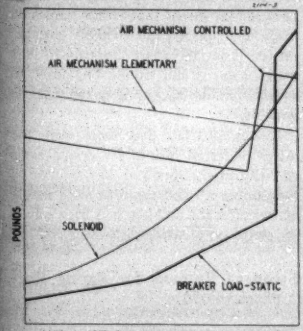


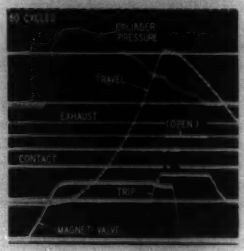
Figure 3. Typical curve of a breaker load and mechanism pull

nism, "Elementary," the pull characteristic would be largely flat, drooping slightly toward the closed position, as the air was expanded into the operating cylinder or dropped in pressure, because of resistance to flow in the connecting passages between the reservoir and the cylinder. Rather than change the breaker levers to co-ordinate the simple air-mechanism pull and the conventional breaker load, a scheme has been worked out to throttle or control the flow of air, and the air-mechanism pull curve takes the general shape of that shown in Figure 3, "Air Mechanism—Controlled."

The principle of the throttle is that when the load is light the air passage is kept small. When the load is about to rise, the throttle is opened by a mechanical linkage, and with the augmented air supply, the stroke is completed with just the right amount of pull to insure positive latching and yet not with excessive slam. Since the throttle is adjustable both as to amount of opening and to position at which it becomes effective, it makes possible the use of one size of mechanism on several types and ratings of breaker.

The throttle is operated through a slotted link, since it is found that full air pressure is required over a greater part of the stroke when fast reclosure is attempted, as compared to that required to complete a simple closing and latching. Under this condition of fast reclosure greater power must be available, first to arrest the opening motion, and then to bring the contacts back to the closed position. The use of a throttled air system of course means the choice of an air pressure and piston area such that the required maximum pull will be secured, but this does not mean that it takes more air than an unthrottled system—rather, that through control, the power availa-

(a). Reclosing in less than 20 cycles



(b). A close-open operation

Figure 4. Oscillograms of breaker timing

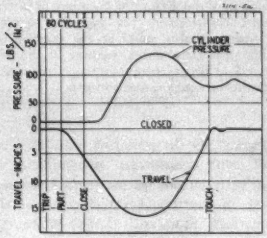
ble is released as demanded by the load, with proper provision made for those operations particularly requiring high speed.

Result of Tests

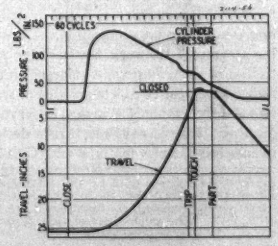
A timing test setup was made on a typical 138-kv oil circuit breaker equipped with an eight-inch compressed-air mechanism of the type described above. Oscillographic records, shown in Figures 4a and 4b show the variation in cylinder pressure, the motion, or travel, of the movable contacts, the motion of the exhaust valve, a battery indication of contact engagement, and the trip-coil and magnet-valve-coil currents. For the sake of clarity the essential data have been traced from these oscillograms and are shown in Figures 5a and 5b.

Figure 5a shows an *OC* operation for which the time from energizing the trip coil to retouching the contact was 19.3 cycles. It will be noted that the magnet valve was energized 4½ cycles after the trip coil, and that the contacts had traveled approximately 36 per cent of the entire stroke at the instant the air valve was opened. The contacts continue opening with reducing speed until there is a cushioned reversal of motion at 57 per cent of the full stroke. The cylinder pressure falls as the contacts travel toward the closed position, due to expansion and throttling. The result is a quick reclosure without excessive strain on the mechanism or pole unit parts, and without excessive slam as the breaker reaches the closed position.

Figure 5b illustrates a *CO* operation using the same breaker and mechanism.



(a). Reclosing in less than 20 cycles



(b). A close-open operation

Figure 5. Clarified speed and pressure records from Figure 4

This test was set up for pretripping, as soon as the auxiliary switch contacts in the trip circuit were made up. Even under this condition the "air-trip-free" action of the mechanism is demonstrated by the fact that there is no back pressure on the operating piston after the first few cycles of travel. A comparison of the opening portion of Figures 5a and 5b shows that at the end of eight cycles after energizing the trip coil, the contact separations exceed that required to interrupt normal short-circuit currents.

Field service throughout a full range of seasonal changes in weather verifies the

Current- and Potential-Transformer Standardization

AIEE COMMITTEE ON PROTECTIVE DEVICES
Current Transformer Subcommittee*

Synopsis: This report has been written to summarize the work of the AIEE current transformer subcommittee and to discuss the considerations which led to the adoption of the material in the revision of section 4, "Instrument Transformers," of the Proposed American Standard for Transformers, *C*-57. Special attention is given to the principles underlying the establishment of the overcurrent requirements of current transformers for relaying service and the revision of the method of specifying the accuracy of instrument transformers for metering service. Mention is also made of the reasons for making other changes, such as in the preferred primary current ratings, potential-transformer ratios, and so forth.

DURING the past two years the current transformer subcommittee of the relay subcommittee revised the section on instrument transformers of the American Standard, *C*-57. When this group was appointed, its assignment was to formulate specifications for current-transformer performance in the overcurrent range for relay application. During the progress of the work, however, the activities of the group were enlarged until they covered the complete revision of section 4 of the Proposed Standard for Transformers. This was the result of a desire to correlate the new material with the old material and to save time and duplication of effort by having the work done by one group. Contacts however were made with the other interested groups so that the work proceeded smoothly with the support and co-operation of these groups. This paper has been written to present the reasons why the material in section 4 is there in its present form.*

Paper 42-116, recommended by the AIEE committee on protective devices, for presentation at the AIEE summer convention, Chicago, Ill., June 22–26, 1942. Manuscript submitted April 13, 1942; made available for printing May 19, 1942.

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Primary Current Rating of Current Transformers (4.021)

The original proposal in the printed draft of *C*-57 contains 29 values of primary current ratings divided into four groups. It was generally felt that this represented an excessive number of ratings and that the number of primary current ratings could be drastically reduced and still adequately cover the field.

The first step was to set up a list of ratings based on one of the sequences in the system of preferred numbers. This gave a list of approximately 16 ratings which covered the range adequately. However, no agreement could be reached upon the values obtained by this simplified method of approach, because certain active ratings were not included and, accordingly, a different method of approach had to be used.

Primary current ratings of 10, 25, 50, 100, 200, 400, and 800 had been established by the joint AEIC-EEI metering group of the association of Edison Illuminating Companies and the Edison Electric Institute, and these ratings were used as a nucleus around which the list now appearing in the standards was established. It was necessary to effect a compromise among the requirements of the groups interested in applying relays, meters, and instruments. Because of the whole-hearted co-operation among the interested groups in reaching a solution which would afford a saving to the industry, the number of preferred primary ratings has been substantially reduced, the reduction being from 29 to 21 ratings.

The preferred primary current ratings are now in one table in paragraph 4.021. It is not the intent that all the values be made available for each circuit voltage; rather, it is the intent that the ratings used for any circuit voltage be limited to as few of values appearing in the table as possible.

It was also felt that there were too many preferred ratings for double-ratio current transformers, and the reduction in the number of values required was a simple matter after the problem had been solved for single-ratio current transformers.

Standard Burdens for Rating Purposes (4.030)

Section 4.030 of the revised standard concerns standard burdens for current transformers, combining and taking the place of the former two sections 4.030 and 4.031 dealing respectively with "Burdens for Current Transformers for Metering Service" and "Burdens for Current Transformers for Relay Service."

Formerly, burdens designated as *X*, *Y*, and *Z*, or 2.5 and 15 volt-amperes at 0.9 power factor, and 50 volt-amperes at 0.5 power factor, respectively, at five amperes and 60 cycles were set as standard metering burdens; then a separate series was set up for relay service as 12.5, 25, 50, 100, and 200 volt-amperes at 0.5 power factor at five amperes and 60 cycles, these burdens to be used for rating purposes.

These two groups have now been combined into one list of standard burdens designated as *B*-0.1, *B*-0.2, *B*-0.5, *B*-1, *B*-2, *B*-4, and *B*-8 corresponding to the ohmic values at 60 cycles of the burden of 0.1 ohm, 0.5 ohm, and so forth. The first three have a burden power factor of 0.9, and the last four have a power factor of 0.5 at 60 cycles. The old meter burden *Y* of 0.6 ohm at 0.9 power factor and the relay burden 0.5 at 0.5 power factor have been replaced by a single burden *B* 0.5, corresponding to 0.5 ohm at 0.9 power factor or 12.5 volt-amperes at 0.9 power factor. There is no essential difference in these three values as far as performance is concerned, but the new value fits into the list of burdens in more orderly fashion.

It was also found necessary to add an additional value of burden; namely, that

* Numbers following subheads refer to paragraphs of the currently proposed revision of section 4 of the Proposed American Standard for Transformers *C*-57 which are given in appendix 3 of this paper.

high degree of reliability obtained in laboratory testing. The flexibility in design and the compactness of the unit obtained by the use of compressed air, and the encouragement gotten from commercial contacts, indicate an increasing demand for this type of mechanism.

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A 2,500,000 Kva Compressed-Air Powerhouse Breaker, L. R. Ludwig, H. M. Wilcox, B. P. Baker. AIEE Transactions, volume 61, 1942, May section, pages 235–41.

designated as *B*-0.2, or five volt-amperes at 0.9 power factor for metering service. This burden is now required for certain current transformers used on low-voltage circuits.

In the revised table then, burdens *B*-0.1, *B*-0.2, *B*-0.5, and *B*-2 are standard burdens for metering service for rating purposes, and burdens *B*-0.5, *B*-1, *B*-2, *B*-4, and *B*-8 are standard burdens for relay service for rating purposes. It should be noted that these burdens also may be designated by the volt-amperes and power factor at five amperes and 60 cycles of each, if the longer designation is preferred. The new designations are different from the old ones in order to avoid confusion with former designations. The proposed values are as shown in paragraph 4.030.

Burdens for Potential Transformers (4.036)

Former section 4.032 concerned standard burdens for potential transformers for rating purposes in all classes of service. This is now included in the revised standard in 4.036. Only one change was made; namely, the volt-amperes of burden *W* was changed from 13 to 12.5 merely so that it would be one half of the value of the *X* burden, which is 25.

Classification of Current Transformers for Accuracy Metering Service (4.031)

Former section 4.033 concerned standard accuracies of current transformers and section 4.035 concerned standard accuracies of potential transformers for metering service. In the revised standard these are included as sections 4.031 for current transformers and 4.037 for potential transformers. Accuracy classes have been specified on a different basis from that previously used. Formerly, fixed limits were assigned separately to ratio error and phase angle for each accuracy class, but on this basis the class designation did not in itself indicate the probable effect of the transformer on the accuracy of measurement of watts or watt-hours.

Since the primary concern with respect to ratio and phase angle of an instrument transformer is the effect on the accuracy of measurement of watts or watt-hours, it is more consistent to use this effect as a criterion of performance, rather than merely the arbitrary ratio error and phase-angle limits which might be chosen. A measure of this effect is the ratio of what a wattmeter would read in a circuit with an instrument transformer having no ratio error or phase angle to what it would read in the same circuit with an instrument transformer having the usual errors. This ratio has been called "transformer correction factor" or TCF, and the standard defines it as "the factor by which the watt-hour meter registration or the watt-meter indication must be multiplied to correct for the error introduced by the transformer through the combined effect of the ratio correction factor (RCF), phase angle (β),* and power factor angle (θ) of the metered load.

Thus for a current transformer (see appendix 1):

$$\text{TCF} = \text{RCF}\frac{\cos\theta}{\cos(\theta-\beta)}$$

At the same time it was also decided to use RCF instead of per cent ratio error.

$$\text{RCF} = \frac{\text{true ratio}}{\text{marked ratio}}$$

The values of TCF for a transformer are dependent upon the power factor of the circuit being measured and the RCF and phase angle of the transformer. Where the transformer angle is small, the relation between these various factors can be expressed in a rather simple manner within accuracy limits sufficiently good for the purpose. By choosing limits for θ and TCF, the limiting values of phase angle and RCF are set. The range of power-factor angle chosen is from 0 to 53 degrees 08 minutes, corresponding to circuit power factor of 1.0 and 0.6 lagging respectively, which covers the usual range of power factors encountered in practice. For these conditions the relation between the limiting values becomes:

For CTs, $\beta = 2{,}600\,(\text{RCF} - \text{TCF})$, in minutes

For PTs, $\gamma = 2{,}600\,(\text{TCF} - \text{RCF})$, in minutes

If ϵ represents the permissible per-unit error in the measurement, it may be positive or negative, and the corresponding limiting values of TCF will be $(1 - \epsilon)$ and $(1 + \epsilon)$. See Figure 1.

The limiting values of TCF as set up in the standard have been chosen entirely from the practical viewpoint of transformer accuracies which are required and those attainable with transformers either of modern or earlier design. The new accuracy classes and, consequently, the limiting values of TCF correspond very closely to the former accuracy classes at circuit power factors at or near 1.0. A new class of wider limits than before has been added to permit an accuracy rating for current transformers with ratio errors in the order of two per cent at 100 per cent rated current such as for certain bushing and similar types.

It will be noted on investigation, for example, that the former 1/4 class results in the limiting TCFs for current transformers at 100 per cent rated current of 0.99365 and 1.00635 in the range of line power factors from 0.6 to 1.0, which produces maximum meter errors of about ± 0.635 per cent. This is more than double the 0.25 per cent error sometimes assumed to be indicated by the former 1/4 class designation, which corresponded to the maximum ratio error only without consideration of phase angle and over-all metering error.

For the new 3/10 class at 100 per cent rated current β varies from $+15.6$ to -15.6 minutes (see Figure 1), the limits of which are 50 per cent greater than formerly for the 1/4 class but which result in only half the maximum possible meter error for that class. It should be noted that this method is the equivalent of that used for the former class *M* only which has been continued as the class 5/10.

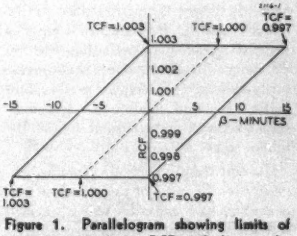


Figure 1. Parallelogram showing limits of ratio correction factor, RCF, and phase angle, β, for a current transformer having a 3/10 accuracy class rating

There accordingly results a means of accuracy rating of instrument transformers for metering service that is of more significance than formerly to the average meterman, since the accuracy class rating is associated directly with the effect of transformer characteristics on the accuracy of measurement. The limits set appear to be practical and adequate for all ordinary purposes, and the method utilized is not involved but provides the necessary rigidity in a simple manner for specification purposes.

Standard Accuracy Classes for Current Transformers for Relaying Service (4.032)

This section, not previously included in the proposed American Standard for

* β is defined as the angle by which the secondary current leads the primary current.

Transformers is the result of an intensive effort to establish standard classes of overcurrent performance. It provides a much needed benchmark for comparison of the performance of various current transformers and for specifying their accuracy at the high currents involved in protective-relay applications. It also establishes in a general way the limits within which a given transformer does not exceed specified errors under overcurrent conditions.

It is important to note that the terms "accuracy" and "performance" as covered by this standard refer to steady-state conditions only. The performance of current transformers under transient conditions is far too complicated to permit of standardization at the present time. While the generalization may be made that the better the steady-state performance, the better the performance will be under transients, nevertheless, it must be realized that adequate performance within the limits of these standards is not necessarily indicative of adequate performance under transient conditions. Reference should be made to the various items of the bibliography.

Current transformers are classified primarily on the basis of the standard burden which each can carry with a specified secondary current without exceeding a specified per cent error. To standardize ratings five amperes has been selected as the standard rated secondary current, and for overcurrent performance the transformers are classified primarily on the basis of their ability at secondary currents of the same value, namely 20 times rated.

Since all the transformers are standardized on the secondary current, the current need not be part of the necessary designation. The designation proposed to identify or express the accuracy classification is, for example, 2.5*H*400 or 10*L*-200. The first number identifies the accuracy class and the limiting per cent error. The letter identifies the type of accuracy classification. The second number identifies the terminal voltage which can be developed on one of the standard burdens at 20 times rated secondary current without exceeding the specified per cent error. This scheme of designation was adopted, because it was expected to give the most useful information.

In the application of relays it is essential that the operating engineer have a knowledge of the performance of the current transformer under overcurrent conditions. While considerable error can frequently be tolerated, it is essential to know the amount of the error or a limiting value which will not be exceeded. This point of view led to the establishment of two accuracy classes for current transformers for relaying service.

In general, the change in the phase angle need not be considered in relaying applications because often it is of no consequence and is relatively small as long as the ratio error is not excessive. Therefore, most attention is focused upon the ratio error. The standard limiting ratio errors are 10 per cent and 2½ per cent, the particular one applicable being indicated by the first figure in the accuracy

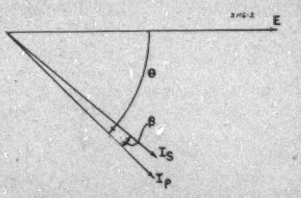


Figure 2. Actual and indicated currents

designation. The figure of 10 per cent has been chosen, both because errors not in excess of this figure can be disregarded in most relay applications, and because for errors in excess of this figure the accuracy of most current transformers falls off very rapidly. The second accuracy class with 2½ per cent as the limit in ratio error has been set up to cover those cases where 10 per cent cannot be tolerated. The error is expressed in per cent of the secondary current.

The overcurrent requirements for current transformers are based upon an overcurrent of 20 times rated in the secondary winding. With a five-ampere rated secondary current, the choice of 20 times rated secondary current is preferable to 20 times rated primary current, because the former results in a secondary current of 100 amperes, which is a convenient number for such purposes.

While the current transformers are classified primarily on the basis of the burden which can be carried at 20 times rated with the rated accuracy, it is desirable to specify, if possible, the burden which can be carried at lesser overcurrents than equal accuracy. An analysis showed that this could be done very simply for transformers of relatively high internal impedance,* such as wound types. Transformers having relatively low internal impedance can be standardized at only one point. Therefore, any method conceived of standardizing the performance at reduced overcurrents for the transformers of relatively low internal impedance, such as bushing type, had serious disadvantages. It was either too complicated or, if simple, necessitated in many cases transformers much larger than would be required to meet only the accuracy requirement at the basic standardizing point of 20 times rated.

In order to capitalize on the ability to standardize the accuracy of the high-internal-impedance types over the range of 5 to 20 times rated secondary current, without penalizing the relatively low-internal-impedance types, two separate classifications have been set up, designated as *H* and *L*. The letter *H* or *L* indicates whether the transformer is classified as a "high-internal-impedance" or a "low-internal-impedance" type. The reason for this distinction is as follows:

The excitation voltage upon which exciting current and consequent ratio error depend is the sum of the secondary terminal voltage plus the internal-impedance drop caused by the secondary current. If the secondary current is reduced from 20 times rated to 5 times rated, but the burden increased inversely, so as to keep the secondary terminal voltage constant, the excitation voltage will decrease due to the reduced internal-impedance drop. The exciting current decreases quite rapidly with a decrease in excitation voltage and for the high-internal-impedance-drop types this effect is great enough that the per cent error tends to remain constant. Thus, for the designs of high-internal-impedance drop, the requirement can be imposed that rated accuracy must be maintained for currents from 5 to 20 times rated with such burdens as to give a terminal voltage no greater than that obtained at 20 times rated current with rated burden. In only relatively few cases will this further requirement increase the size.

Two examples will clarify the meaning of the accuracy designations.

1. A 10*L*400 current transformer is of low internal impedance (as a bushing type). It can carry a *B*-4 burden from one to 20 times rated secondary current, or 5 to 100 amperes, with not over 10 per cent error. It can induce 400 volts with not over ten amperes exciting current.

2. A 2.5*H*200 current transformer is of high internal impedance (as a wound type) capable of supplying a *B*-2 burden at from one to 20 times rated secondary current with not over 2.5 per cent error. It can also supply any standard burden which will not require over 200 volts with secondary currents from 5 to 20 times rated, without exceeding 2.5 per cent error. At 2.5 am-

* The term "internal impedance" is used to identify that elusive characteristic of current transformers through which the exciting current required for a specified secondary induced voltage becomes different for different values of secondary current.

peres on the open-circuit saturation curve the transformer will induce over 200 volts.

Application Data for Current Transformers (4.033)

There is a growing appreciation of the fact that where applicable the saturation-curve method of calculating the performance of current transformers presents a distinct advantage over other methods involving the use of ratio and phase-angle curves. Transformers of the low-internal-secondary-impedance type are susceptible to such treatment. Accordingly, it was thought desirable to establish in the standard application data which shall be available from the manufacturers for use in this connection.

These data should include curves showing the excitation current as a function of the excitation voltage, or volts per turn, together with sufficient data to determine the inphase (watt) component and out-of-phase (magnetizing) component, or the phase angle. The data should also include the resistance of the secondary winding and such information in reference to the internal impedance as may be usable.

Calculations for transformers having low internal impedance may be rather simply made. The initial step is to determine required excitation voltage as based upon the secondary current and the sum of the burden ohms and the secondary resistance.

The exciting current is the maximum error current and may be read directly from the curve, and usually this is all that is required. If the phase angle or a more precise ratio error is required, it may be determined by one of the methods discussed in some of the references in the bibliography. All of these methods use the exciting current in magnitude and position with respect to the excitation voltage, although the mechanics may be different, and they are all essentially a solution of the vector diagram, Figure 3.

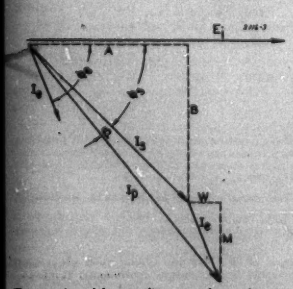


Figure 3. Vector diagram of transformer—low internal secondary impedance type

A few of the methods are given in appendix 2, and it is hoped that experience will indicate a preference for one or the other of these methods.

It is very unfortunate that transformers of the high-internal-impedance type are not directly susceptible to the simple method of calculation, although a somewhat similar method has been proposed. The Standards, therefore, continue the use of the familiar ratio and phase-angle curves for expressing the performance of this type of transformer.

Mechanical Limit for Current Transformers (4.046)

Because the mechanical strength specifications (paragraph 3.050, American Standard *C*-57) of power and distribution transformers is stated in a manner which involves a time element ranging from two to five seconds, it was suggested that the mechanical limit for current transformers should also involve a time element, and one second was suggested. However, the situation is quite different for the two types of transformers; the power or distribution transformer limits the short-circuit current to a definite value, while a current transformer has no appreciable effect in limiting the fault current. Actually, the time element for power and distribution transformers has more concern with the thermal requirement than with the mechanical. If the transformer does not fail within the first few cycles of a fault it will not fail at all mechanically.

There is some opinion that a current transformer may fail mechanically after the crest of the first maximum half cycle has passed, and this has apparently been confirmed to some extent by tests. Also it was quite strongly felt that one second was entirely too long a time in view of the fairly rapid decrement in the fault current. To facilitate testing the current is specified on a symmetrical basis, and it is permitted to cover the time range in successive applications. The proposed requirements are shown in paragraph 4.046.

This paragraph as written includes material which properly belongs in the test code. Due to the lack of a test code at the present time, this material is placed in the standard, because it involves the demonstration of the specifications of mechanical limit. The rated mechanical limit is specified in rms symmetrical amperes, coupled with the stipulation that the transformer must withstand the forces produced by this value of current when the current wave is completely offset. In testing this may be demonstrated by a symmetrical wave of twice the value of the rated mechanical limit maintained for the specified time of six cycles; or it may be demonstrated by successive applications of current with no intentional delay between applications, in which case the crest current may be measured for the final significant cycle of each application and must not be less than twice the crest corresponding to the crest of the rated mechanical limit.

Open Secondary Circuit of Current Transformers (4.047)

The original *C*-57 simply required that current transformers operate with the secondary circuit open "without damage to the transformer." In many cases the strict interpretation of this rule resulted in an abnormal design without any compensating features. Accordingly it was thought better to correlate the requirement for this condition with the test on the secondary windings. The proposed requirements are shown in paragraph 4.047.

Preferred Ratios for Potential Transformers (4.020) and Standard Insulation Classes and Tests for Potential Transformers (4.050)—Table IX

The question of what insulation test was standard for a potential transformer of a given ratio for circuits below 15 kv was the cause of many misunderstandings. The solution of this problem consisted of combining the tabulation of preferred ratios with the tabulation of insulation classes and tests.

When the preparation of *C*-57 was first begun, it was recognized that certain instrument transformers had impulse levels one step lower than those being considered for the circuit voltages with which the transformers were being used, although they could withstand the proposed low-frequency test required for these same circuit voltages. The circuit voltages in question were in the 5.0-, 8.7-, and 15-kv classes, and to take care of this situation note *c*, reading as follows, was proposed:

"(*c*) Indoor instrument transformers are available in the 2.5-, 5-, 8.66-, and 15-kv classes insulated one level lower than the values of this tabulation."

This note was the cause of great confusion, because its wording permitted misinterpretation, and in the printed draft of *C*-57 it was interpreted as applying to the lower-frequency test also. It resulted in a line of potential transformers having ratios 20:1, 40:1, and 60:1,

which had impulse insulation levels corresponding to the present insulation classes 2.5, 5.0, and 8.66, respectively. These transformers, according to the present standard, cannot however be connected in wye for use between line and neutral at their rated excitation voltage, because they are not insulated for this service. Because of this, there has been considerable effort to eliminate them entirely from the standard. However, these transformers represent existing practice and are used extensively, particularly for metering applications. Placing them in the table and associating their ratios with their proper insulation class permits their continued use and eliminates the possibility of confusing them with the trans-

Preferred Ratios Standard Insulation Classes and Dielectric Tests for Potential Transformers

Table IX of Proposed Standard C-57

Insulation Class (Name-Plate Rating) Col. 1[a]	Preferred Ratio Col. 2[b]	Rated Voltage		Normal Circuit Voltage on Which Transformers May Be Used		Dielectric Tests			
						Low Frequency	Impulse		
							Chopped Wave		Full Wave
		Secondary Volts Col. 3[b]	Primary Winding (Name-Plate Rating) Col. 4	When Δ Connected Volts Col. 5[b,c]	When Y-Connected Volts Col. 6[a,d,e]	Kv RMS Col. 7[f]	Kv Crest Col. 8[f]	Minimum Time to Flashover μsec. Col. 9[f]	Kv Crest Col. 10
1.2	1–1	120	120	120	208	10	36	1.0	30
	2–1	120	240	240	416	10	36	1.0	30
	4–1	120	480	480	832	10	36	1.0	30
	5–1	120	600	600	1,040	10	36	1.0	30
2.5	20–1	120	2,400	2,400	2,400	15	54	1.25	45
5.0	20–1	120	2,400/4,160 Y	2,400	4,160	19	69	1.5	60
	40–1	120	4,800	4,800	4,800	19	69	1.5	60
8.66	35–1	120	4,200/7,280 Y	4,200	7,200	26	88	1.6	75
	40–1	120	4,800/8,320 Y	4,800	8,320	26	88	1.6	75
	60–1	120	7,200	7,200	7,200	26	88	1.6	75
15L	60–1	120	7,200/12,480 Y	7,200	12,000	34	110	1.8	95
	70–1	120	8,400/14,560 Y	8,400	14,400	34	110	1.8	95
	100–1	120	12,000	12,000	12,000	34	110	1.8	95
	120–1	120	14,400	14,400	14,400	34	110	1.8	95
15 H	60–1	120	7,200/12,480 Y	7,200	12,000	34	130	2.0	110
	70–1	120	8,400/14,560 Y	8,400	14,400	34	130	2.0	110
	100–1	120	12,000	12,000	12,000	34	130	2.0	110
	120–1	120	14,400	14,400	14,400	34	130	2.0	110
25	200/115–1	69.3/120	13,800/24,000 Y	—	24,000	51	175	3.0	150
	200–1	120	24,000	24,000	24,000	51	175	3.0	150
34.5	300/173–1	66.4/115	19,900/34,500 Y	—	34,500	70	230	3.0	200
	300–1	115	34,500	34,500	34,500	70	230	3.0	200
46	400/231–1	66.4/115	26,600/46,000 Y	—	46,000	93	290	3.0	250
	400–1	115	46,000	46,000	46,000	93	290	3.0	250
69	600/346–1	66.4/115	39,800/69,000 Y	—	69,000	140	400	3.0	350
	600–1	115	69,000	69,000	69,000	140	400	3.0	350
92	800/462–1	66.4/115	53,100/92,000 Y	—	92,000	185	520	3.0	450
	800–1	115	92,000	92,000	92,000	185	520	3.0	450
115	1,000/577–1	66.4/115	66,400/115,000 Y	—	115,000	230	630	3.0	550
	1,000–1	115	115,000	115,000	115,000	230	630	3.0	550
138	1,200/693–1	66.4/115	79,700/138,000 Y	—	138,000	275	750	3.0	650
	1,200–1	115	138,000	138,000	138,000	275	750	3.0	650
161	1,400/809–1	66.4/115	93,000/161,000 Y	—	161,000	325	865	3.0	750
	1,400–1	115	161,000	161,000	161,000	325	865	3.0	750
196	1,700/982–1	66.4/115	113,100/196,000 Y	—	196,000	395	1,035	3.0	900
	1,700–1	115	196,000	196,000	196,000	395	1,035	3.0	900
230	2,000/1,155–1	66.4/115	132,800/230,000 Y	—	230,000	460	1,210	3.0	1,050
	2,000–1	115	230,000	230,000	230,000	460	1,210	3.0	1,050
287.5	2,500/1,444–1	66.4/115	166,000/287,500 Y	—	287,500	575	1,500	3.0	1,300
	2,500–1	115	287,500	287,500	287,500	575	1,500	3.0	1,300
345	3,000/1,733–1	66.4/115	199,200/345,000 Y	—	345,000	690	1,785	3.0	1,550
	3,000–1	115	345,000	345,000	335,000	690	1,785	3.0	1,550

[a] Intermediate voltage ratings are placed in the next higher insulation class unless otherwise specified.

[b] Two types of potential transformers are available in insulation classes 25 kv and above. One type is for primary line-to-neutral connection and is provided with a tapped secondary winding, or with two secondary windings, to make available nominal 115 or 120 secondary volts when connected Y or Δ. These transformers are designated in Col. 2 by the double ratio, for example 300/115:1. The other type is for primary line-to-line connection to make available 115 or 120 secondary volts from each transformer. These transformers are designated in Col. 2 by the single ratio, for example 200:1.

[c] When transformer apparatus is used on a Δ-connected system which operates with one phase grounded, special consideration should be given to the selection of the insulation class.

[d] Y-connected transformers for operation with neutral solidly grounded, or grounded through an impedance, may have reduced insulation at the neutral as specified in 2.031.

[e] All potential transformers for Y connection on a three-phase three-wire ungrounded or impedance-grounded system (or on a four-wire system where the ground may be disconnected during a line-to-ground fault) should be designed to have magnetic induction low enough to enable them to operate continuously at line-to-line voltage.

[f] The secondary windings of instrument transformers shall withstand a low-frequency test of 2,500 volts to ground and normally grounded core and other metal parts but no impulse tests are required. See notes (g) and (i) of Table II.

formers of the same ratio having the higher test which may be connected in wye at their rated excitation voltage.

In the proposed initial draft of American Standard *C*-57, the ratios of potential transformers intended for line-to-neutral connection did not give 115 volts line-to-neutral in all cases when connected wye at the rated voltages indicated. This was felt to be an undesirable situation, and these ratios were adjusted slightly to correct this condition. A double-ratio rating was also given to provide for 115-volt line-to-line as well as line-to-neutral connection.

The new proposal in Table IX is given here under the same table number. The third column, "Secondary Volts," has been added to make clear which transformers have two secondary voltages available. In the fourth column the item, "Name-Plate Rating," has been added to the heading, together with the proper entries in the column, to eliminate the previous confusion which existed as to which transformers were suitable only for line-to-neutral connection. The fifth and sixth columns were added to indicate the circuit voltage for which the transformers were intended. The seventh column was added to point out the limit voltages between line terminal and ground for steady-state operation.

Standard Insulation Classes and Tests for Current Transformers (4.051)

In the initial proposed draft of *C*-57, the insulation tests for current transformers were included in the same table as tests for potential transformers. This obviously led to much confusion and misunderstanding which has been overcome by the use of a separate table for the insulation tests for current transformers. The proposal is given as Table X.

Bushing-Type Current Transformers

The printed draft of *C*-57 did not include any material on bushing-type current transformers. It was felt that this should be done, and wherever practicable, bushing-type current transformers have been covered, but not as completely as could be desired.

Name Plates (4.075)

A new item, "Data Sheet Number," has been added to the required information on name plates. This was done, because in many cases the name plate will not be large enough to include all the information which might be thought desirable. It is the intent that the manufacturer shall have such material available under this number and will be able to furnish it upon request by reference to the proper design number.

It is expected that the "Data Sheet Number" will serve the same general purpose as the instruction book or sheet referred to in 3.090 (16). The "Data Sheet" will be the means whereby the user may obtain such information as thermal and mechanical limits, accuracy classifications, application data, or any other information of general use in the application of instrument transformers.

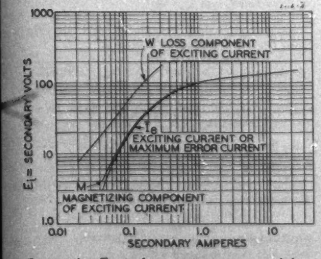


Figure 4. Typical saturation curve and loss and magnetizing component curves of a bushing-type current transformer

60 cycles
Nominal ratio 500/1
Secondary winding resistance 0.19 ohm

Appendix I. Development of Expression of Limiting Phase Angle β

In Figure 2 are shown the actual and indicated currents in a current transformer on a 1–1 turn basis. The relationship among the transformer correction factor, TCF, the ratio correction factor, RCF, and the phase angle, β, is developed as follows on the assumption that there is no error in the potential circuit:

$$\text{Actual power} = EI \cos \theta$$

$$\text{Indicated power} = EI_s \cos (\theta - \beta)$$

$$\frac{\text{Actual power}}{\text{Indicated power}} = \frac{I_p}{I_s} \frac{\cos \theta}{\cos (\theta - \beta)}$$

Standard Insulation Classes and Dielectric Tests for Current Transformers

Table X of Proposed Standard C-57

Insulation Class (Name-Plate Rating) Col. 1[a]	Maximum Line-to-Line Voltage (Kv) Col. 2	Dielectric Tests: Low Frequency Kv RMS Col. 3[b]	Dielectric Tests: Impulse, Chopped Wave Kv Crest Col. 4[b]	Dielectric Tests: Impulse, Chopped Wave Minimum Time to Flashover μsec. Col. 5[b]	Dielectric Tests: Impulse, Full Wave Kv Crest Col. 6[b]
1.2	1.2	10	36	1.0	30
2.5	2.5	15	54	1.25	45
5.0	5.0	19	69	1.5	60
8.66	8.66	26	88	1.6	75
15Z	15.0	34	110	1.8	95
15*H*	15	34	130	2.0	110
25	25	51	175	3.0	150
34.5	34.5	70	230	3.0	200
46	46	93	290	3.0	250
69	69	140	400	3.0	350
92	92	185	520	3.0	450
115	115	230	630	3.0	550
138	138	275	750	3.0	650
161	161	325	865	3.0	750
196	196	395	1,035	3.0	900
230	230	460	1,210	3.0	1,050
287	287	575	1,500	3.0	1,300
345	345	690	1,785	3.0	1,550

[a] Intermediate voltage ratings are to be placed in the next higher insulation class unless specified otherwise.

[b] The secondary windings of instrument transformer shall withstand a test of 2,500 volts to ground and normally grounded core and other metal parts. No standard impulse tests have been established for secondary windings of instrument transformer.

But

$$\frac{\text{Actual power}}{\text{Indicated power}} = \text{TCF by definition}$$

$$\frac{I_p}{I_s} = \text{RCF by definition}$$

so that

$$\text{TCF} = \text{RCF} \frac{\cos \theta}{\cos (\theta - \beta)}$$

$$= \text{RCF} \frac{\cos \theta}{\cos \theta \cos \beta + \sin \theta \sin \beta}$$

A positive angle β indicates in this development that the secondary current is

Table A

Primary Current Rating	Preferred Ratio
(a) Single-ratio current transformers	
10	2–1
15	3–1
20	4–1
25	5–1
30	6–1
40	8–1
50	10–1
75	15–1
100	20–1
150	30–1
200	40–1
300	60–1
400	80–1
600	120–1
800	160–1
1,200	240–1
1,500	300–1
2,000	400–1
3,000	600–1
4,000	800–1
5,000	1,000–1
(b) Double-ratio current transformers	
10/20	2/4–1
25/50	5/10–1
50/100	10/20–1
75/150	15/30–1
100/200	20/40–1
150/300	30/60–1
200/400	40/80–1
300/600	60/120–1
400/800	80/160–1
600/1,200	120/240–1
(c) Multiratio transformers (bushing type)	
600*	120/100/90/80/60–1
	50/40/30/20/10–1
1,200*	240/200/180/160/120–1
	100/80/60/40/20–1
2,000*	400/360/320/280–1
	240/160–1
3,000*	600/400/320–1
4,000*	800/600/400–1
5,000*	1,000/800/600–1

* Maximum.

ahead of the primary current, from which the following close approximation is obtained:

$$RCF = TCF(1+\beta \tan \theta) \quad (\beta \text{ in radians})$$

and then

$$\beta = (RCF - TCF) \cot \theta \quad (\beta \text{ in radians})$$

The value of the phase angle β in minutes is given by

$$\beta = 3{,}438 \cot \theta \, (RCF - TCF)$$

For a given power-factor angle θ, phase angle β and ratio correction factor RCF, the value of the transformer correction factor TCF at this condition will not be exceeded for angles less than this value of θ.

Since the maximum angle θ in the transformer accuracy limits is taken as $\cos^{-1}0.6$, then these TCF limits will not be exceeded for any value of θ from $\cos^{-1}0.6$ to $\cos^{-1}1.0$.

With $\cos^{-1} 0.6$

$$\beta = 2{,}600 \, (RCF - TCF) \text{ very nearly}$$

in which both the maximum and minimum values of β, RCF, and TCF are taken for the purpose of specifying their limits.

Table B

Designation of Burden*	Burden Characteristics: Resistance (Ohms)	Burden Characteristics: Inductance (Millihenrys)	Secondary Burden at 60 Cycles and Five Amperes Secondary Current: Impedance (Ohms)	Secondary Burden at 60 Cycles and Five Amperes Secondary Current: Volt-Amperes*	Secondary Burden at 60 Cycles and Five Amperes Secondary Current: Power Factor
B-0.1 (*X*)	0.09	0.116	0.1	2.5	0.9
B-0.2	0.18	0.232	0.2	5.0	0.9
B-0.5 (*Y*)	0.45	0.580	0.5	12.5	0.9
B-1	0.5	2.3	1.0	25	0.5
B-2 (*Z*)	1.0	4.6	2.0	50	0.5
B-4	2.0	9.2	4.0	100	0.5
B-8	4.0	18.4	8.0	200	0.5

* In accordance with 1.130 the burden may also be designated by means of the volt-ampere characteristic: that is, va 2.5, or va 50.

Table C

Accuracy Class	Limits of Transformer Correction Factor: 100 Per Cent Rated Current: Minimum	100 Per Cent Rated Current: Maximum	10 Per Cent Rated Current: Minimum	10 Per Cent Rated Current: Maximum	Limits of Power Factor (Lagging) of Metered Power Load
2.4	0.976	1.024	0.952	1.048	0.6–1.0
1.2	0.988	1.012	0.976	1.024	0.6–1.0
6/10	0.994	1.006	0.988	1.012	0.6–1.0
3/10	0.997	1.003	0.994	1.006	0.6–1.0
5/10	0.995**	1.005**	0.995	1.005	0.6–1.0

** These values also apply to 150 per cent of rated current.

Appendix 2. Calculation of Current-Transformer Ratio-Correction Factor and Phase Angle

Method 1

Starting with a given value of secondary current I_s, determine the internal voltage E_i necessary to force the secondary current I_s through the secondary resistance R_s in series with the external burden Z_b, and the angle ϕ_i by which I_i lags E_i. Express the secondary current vectorially with respect to E_i as a reference.

$$I_s = A - jB$$

From the curve such as Figure 4, determine the exciting current as a vector with respect to same reference voltage E_i.

$$I_e = W - jM$$

Determine the primary current, on the same turn base, by adding vectorially the secondary and exciting currents.

$$I_p = \sqrt{(A+W)^2 + (B+M)^2}$$

$$RCF = I_p / I_s$$

Phase angle β is the angle by which I^s leads I_p

$$\beta = \left(\tan^{-1}\frac{B+M}{A+W}\right) - \phi_s, \text{ in degrees}$$

Table D

Accuracy Class	Limits of Transformer Correction Factor	Limits of Power Factor (Lagging) of Metered Power Load
1.2	1.012–0.988	0.6–1.0
6/10	1.006–0.994	0.6–1.0
3/10	1.003–0.997	0.6–1.0

Table E

Maximum Per Cent Ratio Error	Accuracy Class	Maximum Per Cent Ratio Error	Accuracy Class	Maximum Secondary Terminal Volts*	Maximum Secondary Burden Ohms**
10	10 *H*50	2.5	2.5 *H*50	50	2
10	10 *H*100	2.5	2.5 *H*100	100	4
10	10 *H*200	2.5	2.5 *H*200	200	8
10	10 *H*400	2.5	2.5 *H*400	400	16
10	10 *H*800	2.5	2.5 *H*800	800	32

* Secondary voltage and current limitation—in any accuracy class the specified per cent ratio error shall not be exceeded for the specified secondary terminal voltage at current values from 5 to 20 times rated secondary current.

** Secondary burden and current limitation—in any accuracy class the specified per cent ratio error shall not be exceeded for the specified secondary burden ohms at current values from one to five times rated secondary current.

Method 2

Express the secondary current as

$$I_s = I_s \epsilon^{j\phi_s}$$

and the excitation current as

$$I_e = I_e \epsilon^{j\phi_e}$$

From these the RCF is

$$RCF = \sqrt{1 + 2\frac{I_e}{I_s}\cos(\phi_e - \phi_s) + \left(\frac{I_e}{I_s}\right)^2}$$

And β, the angle by which I_s leads I_p is, providing ϕ_e and ϕ_s are looked upon as being positive angles

$$\tan \beta = \frac{I_e \sin(\phi_e - \phi_s)}{I_s + I_e \cos(\phi_e - \phi_s)}$$

RCF and β may be determined directly from the chart given in Figure 5.

Method 3

Let I_p, I_e, ϕ_p, and ϕ_e be the same as in method 2 and let

$$a = \frac{I_e}{I_s} \text{ and } p = a\cos(\phi_e - \phi_s) + \frac{a^2}{2}$$

Then the ratio correction factor

$$RCF = 1 + p - \frac{p^2}{2} + \frac{p^3}{2} - + \text{etc.}$$

And the phase angle β, by which I_s leads I_p is, providing ϕ_e and ϕ_s are looked upon as positive angles

$$\tan \beta = \frac{a \sin(\phi_e - \phi_s)}{1 + a\cos(\phi_e - \phi_s)}$$

Appendix 3. Excerpts From Proposed American Standard for Transformers C-57 (Currently Proposed Revision of Section 4)

4.021 PREFERRED PRIMARY CURRENT RATINGS AND RATIOS OF CURRENT TRANSFORMERS

The preferred primary current ratings and ratios of current transformers shall be as shown in Table A.

Standard Burdens and Standard Accuracy Classes for Current Transformers

4.030 STANDARD BURDENS FOR RATING PURPOSES

(*a*). Standard burdens for rating purposes shall have constant-impedance ohms and linear-reactance characteristics over the entire current range on which they are used and shall have resistance and inductance values, together with impedance and volt-ampere values, at 60 cycles as shown in Table B.

(*b*). Burden *B*-0.1, *B*-0.5, and *B*-2 are standard burdens for current transformers used for metering service and correspond to the *X*, *Y*, and *Z* designation previously used. Burdens *B*-0.2 and *B*-0.5 are new standard burdens for metering service.

Burdens *B*-5, *B*-1, *B*-2, *B*-4, and *B*-8 are standard burdens for current transformer used for relaying service.

4.031 STANDARD ACCURACY CLASSES OF CURRENT TRANSFORMERS FOR METERING SERVICE

(*a*). The accuracy classification of current tranformers for metering service shall be based on the requirement that the transformer correction factor (TCF) shall be within specified limits over a specified range of power factor of the load being metered.

For the purpose of these standards the term "Transformer Correction Factor" (TCF) is used instead of the more complete term "Instrument Transformer Correction Factor" defined in 1.134 to designate the factor by which the watt-hour meter registration or the wattmeter indication must be multiplied to correct for the error introduced by the transformer through the combined effect of the ratio correction factor (RCF) and phase angle *B*.

(*b*). For purposes of standardization the limits of transformer correction factor shall be specified at 100 per cent of rated primary current and at 10 per cent of rated primary current.

(*c*). For the purposes of accuracy classification, the rated secondary current shall be five amperes.

(*d*). The standard accuracy classes and corresponding limits of transformer correction factor (TCF) shall be as shown in Table C.

(*e*). For any known ratio correction factor (RCF) of a given transformer, the positive and negative limiting values of the phase angle β in minutes may be expressed as follows:

$$\beta = 2{,}600(\mathrm{RCF} - \mathrm{TCF})$$

in which TCF is taken as the minimum and maximum transformer correction factor specified in (*d*) above.

The limiting values of the ratio correction factor are the same as the limits of transformer correction factor given in (*d*) above since the phase angle of the current transformer does not introduce a significant error when it is small and when the load power factor is 1.0. These limits of ratio correction factor, together with the corresponding limits of phase angle, keep the transformer correction factor within the specified limits for all values of power factor (lagging) of the measured power load between 0.60 and 1.00.

(*f*). A current transformer shall be given an accuracy rating in accordance with the accuracy class (or classes) in which it falls for the specified standard burden (or burdens). Double-ratio transformers shall be given accuracy ratings for each ratio.

(*g*). In practice, current transformers shall be designated in reference to accuracy rating by the accuracy class number followed by the burden number. For example 6/10 *B*-2 and/or 5/10 *B*-0.1 and so forth.

4.037 STANDARD ACCURACY CLASSES FOR POTENTIAL TRANSFORMERS FOR METERING SERVICE

(*a*). The accuracy classification of potential transformers for metering service shall be based on the requirement that the transformer correction factor (TCF) shall be within specified limits over a specified range of power factor of the load being metered [see paragraph 4.031 (*d*)].

(*b*). Standard output and accuracy ratings of potential transformers shall be on the basis of their standard rated secondary voltage.

(*c*). The standard accuracy classes and corresponding limits of transformer correction factor for potential transformers shall be as shown in Table D.

(*d*). For any known ratio correction factor (RCF) of a given transformer, the positive and negative limiting values of the phase angle "β" in minutes may be expressed as follows:

$$\gamma = 2{,}600(\mathrm{TCF} - \mathrm{RCF})$$

in which TCF is taken as the maximum and minimum transformer correction factor specified in (*c*).

The limiting values of the ratio correction factor are the same as the limits of the transformer correction factor, since the phase angle of the potential transformer does not introduce a significant error when it is small and when the load power factor is 1.0. These limits of ratio correction factor, to-

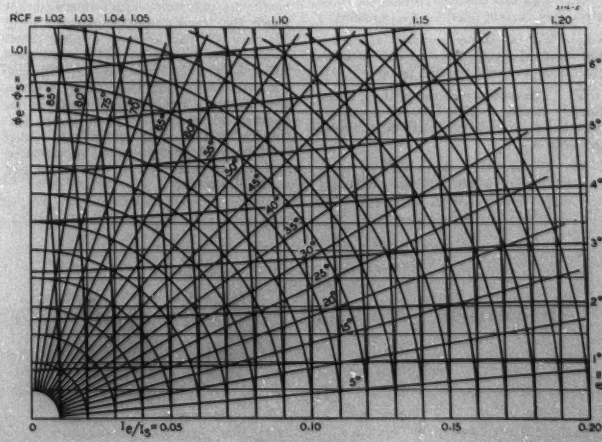
Table F

Maximum Per Cent Ratio Error	Accuracy Class	Maximum Exciting Current	Maximum Per Cent Ratio Error	Accuracy Class	Maximum Exciting Current	Maximum Secondary Terminal Volts*	Maximum Secondary Burden**
10	10*L*50	10	2.5	2.5*L*50	2.5	50	*B*-0.5
10	10*L*100	10	2.5	2.5*L*100	2.5	100	*B*-1
10	10*L*200	10	2.5	2.5*L*200	2.5	200	*B*-2
10	10*L*400	10	2.5	2.5*L*400	2.5	400	*B*-4
10	10*L*800	10	2.5	2.5*L*800	2.5	800	*B*-8

* Secondary voltage and current limitation—in any accuracy class the specified per cent ratio error shall not be exceeded for the specified secondary terminal voltage at 20 times rated secondary current.

** Secondary burden and current limitation—in any accuracy class the specified per cent ratio error shall not be exceeded for the specified secondary burden ohms at current values from 1 to 20 times rated secondary current.

Figure 5. Chart for calculating RCF and β



gether with the corresponding limits of phase angle, keep the transformer correction factor within the specified limits for all values of power factor (lagging) of the measured power load between 0.6 and 1.0.

(*e*). These limits shall apply from 10 per cent above rated voltage to 10 per cent below rated voltage, at rated frequency, and from no burden on the potential transformer to the specified burden (see paragraph 4.002).

(*f*). In practice, a potential transformer shall be designated as 6/10 *W* if its ratio and phase-angle characteristics conform with the requirements of accuracy class 6/10 when used with any secondary burden not exceeding *W* with the power factor specified for *W* burden.

(*g*). In plotting curves of potential transformer accuracy, power factors shall be chosen to conform with the power factors of the standard burdens.

4.032 Standard Accuracy Classes for Current Transformers for Relaying Service

(*a*). 1. The overcurrent performance of current transformers for relaying service shall be specified on the basis of a standard per cent ratio error at 20 times rated secondary current, the standard relaying burdens, and the secondary terminal voltages established by the specified secondary current (20 times rated) operating into these burdens.

In these standards the term "per cent ratio error" is defined as 100(RCF−1), RCF = ratio correction factor.

2. A current transformer shall be given an accuracy rating in accordance with the maximum secondary terminal voltage at which the specified error will not be exceeded on the basis of 20 times normal secondary current operating into a standard relaying burden.

3. Accuracy classification for multiratio current transformers shall be given for the maximum secondary winding, and for double-ratio transformers shall be given for each ratio.

(*b*). Unless otherwise specified the rated secondary current shall be five amperes.

(*c*). For the purposes of standardization the standard specified per cent ratio errors shall be 10 per cent and 2½ per cent.

(*d*). The accuracy classes of those transformers having a high internal secondary impedance (wound-type) shall be as shown in Table E.

(*e*). The accuracy classes of those transformers having a low internal secondary impedance (bushing-type) shall be as shown in Table F.

(*f*). The induced secondary voltage and corresponding value of exciting current form a good criterion of transformer performance and burden capacity. The induced secondary voltage is the vector sum of the secondary terminal voltage and the voltage drop due to the internal impedance of the secondary winding. The internal impedance may be negligible in certain designs, such as the bushing type, and quite large in others, such as the wound type.

Transformers having a relatively high internal impedance can maintain constant secondary terminal voltage under load for a range of 5 to 20 times rated secondary current, due to the fact that the internal voltage drop decreases more rapidly with reduction in secondary load current than the induced secondary voltage decreases with lower values of exciting current.

Transformers having relatively low internal impedance do not as a rule have this compensating internal voltage drop and can be standardized at one point only.

Recognition of this fact has resulted in the establishment of separate accuracy specifications for the two forms of current transformers.

(*g*). In practice, current transformers shall be designated by the accuracy class number.

The first number indicates the per cent ratio error. The letter *H* or *L* indicates which type of accuracy is specified. The second number gives the maximum secondary voltage at which the specified accuracy is obtained, with a secondary current of 20 times rated.

For example, a transformer of the 10*H*400 accuracies class has high internal impedance and the ratio error is not more than ten per cent at a secondary terminal voltage not exceeding 400 volts for secondary current values from 25 amperes to 100 amperes, or from 5 times to 20 times rated current.

4.046 Mechanical Limit for Current Transformers

(*a*). The mechanical limit of a current transformer is defined by specifying the maximum rms symmetrical primary current which the transformer is capable of withstanding with its secondary winding short-circuited for six cycles (0.1 second) and which may be in successive applications with no intentional time delay between applications. Transformers shall not be required to withstand a test for the mechanical limit exceeding one-half the thermal limit at six cycles (0.1 second) as calculated from the thermal limit at one second [see section 4.045 (*d*)].

(*b*). The transformer shall be capable of withstanding the mechanical forces produced by this value of current when the current wave is initially completely offset.

4.047 Open Secondary Circuit of Current Transformers

Current transformers conforming to these standards shall be capable of carrying rated primary current continuously with the secondary circuit open, without damage to the transformers, except when the open-circuit voltage exceeds 3,500 volts crest, which usually will occur when the ratio exceeds 300–1. When the secondary peak voltage exceeds 3,500 volts, the secondary of such a transformer shall be insulated so that it can operate continuously with current in the primary to produce 3,500 volts peak across the secondary terminals. (However, the operation of current transformers under such conditions should be guarded against to prevent excessive voltage in the secondary winding.)

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